

**Groundwater chemistry and supplementary sources of
freshwater in Arid environments:**

Groundwater salinisation, solar desalination & fog collection

by

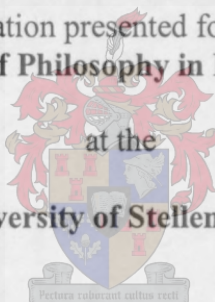
Shanyengana E. Shanyengana

MSc Environmental Engineering
(KTH Stockholm, Sweden)

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University of Stellenbosch



Promoters:

Prof. Dr. R.D. Sanderson

Director,

UNESCO Associated Centre for Macromolecules and Materials

University of Stellenbosch

Chemistry Department,

Polymer Science Division

Private Bag X1, Matieland 7602

Stellenbosch, South Africa

<http://www.sun.ac.za/unesco/unesco.htm>

Prof. Dr. M.K. Seely

Director,

Desert Research Foundation of Namibia

P O Box 20232

Windhoek,

Namibia


<http://www.drfn.org>

Stellenbosch

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DECLARATION

I, the undersigned hereby declare that the work contained in this dissertation is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

 Signature

Date

ABSTRACT

Freshwater is the most fundamental of all life-supporting resources that determine our social, economic and political wellbeing. It is, however, only a small percentage of the world's water resources and is also unevenly distributed. Arid regions make-up about forty percent of the world's land area and have a large proportion of the world population, however, they only have a small fraction of the freshwater compared to other areas.

Conventional freshwater sources in arid environments such as surface water in rivers, lakes and dams are often seasonal, available mainly during the rainy season. Equally, only a small part of the rain (0 - 5% of rainfall) infiltrates into groundwater reserves, and even this groundwater displays high rates of salinisation such that the end-water is too saline for human consumption.

The poor quality of groundwater in arid regions is generally understood, however, it is always assumed that this is mainly a problem in areas where surface water does not occur. The study investigates seasonal groundwater salinisation in ephemeral (seasonal) river sources in some parts of Namibia and aims to derive a better understanding of the nature of this problem and how it affects people in these areas. It also looks at some possible solutions to the problem with the aim of informing water managers and scientists who are responsible for formulating solutions for water supply to areas in arid regions.

These solutions are designed to take advantage of available opportunities in the study areas namely; the abundant supply of solar energy, alternative sources of freshwater such as fog and general atmospheric moisture, and adaptations for water collection in animals that inhabit these regions.

The results show that groundwater in shallow ephemeral river sources of the Namib Desert and the Cuvelai delta in North central Namibia display high seasonal variation in Total Dissolved Solids (TDS) and chemical composition. The lowest TDS values are recorded during the rainy season, mainly after the first rains in the high rainfall areas and only after flood events in the lower rainfall regions. The groundwater salinity increases during the remainder of the year and in most cases becomes too saline for drinking purposes.

The investigations of possible solutions indicate that small-scale photovoltaic reverse osmosis; solar distillation and fog collection could be used to address the seasonal shortage of potable water in these areas. The low-pressure (6 bar) reverse osmosis desalination experiments show that it is possible to operate the unit on a solar-driven pump to produce enough water to cover the typical daily water demand of a village in the Namib Desert. This unit would produce about 4600 litres per day (l/day) of 500-mg/l TDS product water, which exceeds the water production of similar world-leading small-scale RO units in Australia and The Canary Islands.

The results also show that the cost of solar distillation units (solar stills) can be reduced sufficiently to make them a viable option for water supply to individual households in these rural areas.

The study also found that fog is a feasible alternative source of freshwater in some of the study areas. The fog water is generally of 'A' quality drinking water according to the WHO-derived Namibian Drinking Water Quality Guidelines (NDWQG) and can be used directly or mixed with the saline groundwater to provide potable water. Mixing of the above-mentioned waters is particularly suitable in the Central Namib Desert because the period of high groundwater salinity coincides with that of peak fog deposition.

The results also show that fog water can be collected with various polymeric greenhouse shade netting that can be easily obtained, and provides guidelines on the correct percentage shade coefficient and weave of possible fog collector mesh to intending users of fog collection technology in areas where the polypropylene mesh that is used in Standard Fog Collectors is not available.

The investigations of surface properties of fog-harvesting beetles and experiments with various prototype collectors show that it is possible to increase water production in fog collectors existing today. The hydrophobic surface conditions as were found on the cuticles of fog-basking beetles (*Onymacris unguicularis* and *Onymacris bicolor*) would enhance formation and runoff of large fog droplets on the collector surface. The prototype extractor-fan- and cooling system-based collectors show that it is possible to increase fog collection on polymeric meshes about three times and also that a comparable volume of atmospheric moisture can be collected even when there is no fog, up to a relative humidity of about 40%.

In conclusion the study emphasizes that groundwater salinity in arid regions is at times a seasonal problem that should be considered in water supply strategies for these regions. Also that atmospheric moisture is a feasible alternative source of freshwater in some arid regions that often exceeds rainfall several times and should be considered as an important aspect of the strategies to address water problems in these areas. The study strongly recommends that scientists, engineers and water managers in these regions should always investigate the available opportunities such as climatic conditions (e.g. fog deposition) and adaptations for water collection/conservation that are found in the endemic plants and animals in order to develop sustainable solutions to this problem. They should also constantly update themselves on developments/opportunities that arise in the larger water industry that could be of benefit to water supply initiatives for remote areas in developing countries.

Lastly, the study serves to better the understanding of the nature of groundwater salinity in arid environments that are dependent on seasonal surface flow for water supply as well as to contribute to the formulation of solutions to this problem in these areas, particularly in west coast hyper arid environments where conventional sources of freshwater are most inadequate. It also emphasises the role of materials science (polymers) and environmental engineering as well as that of UNESCO associated scientific institutions in the formulation of sustainable solutions to some of the current water problems in arid regions.

Keywords: *Arid lands, hydrochemistry, sources of freshwater, desalination, atmospheric moisture*

OPSOMMING

Vars water is die mees fundamentele van alle lewensonderhoudende natuurlike hulpbronne wat ons sosiale, ekonomiese, en politieke welstand bepaal. Dit is egter slegs 'n klein gedeelte van die totale waterbronne van die wêreld, en is boonop baie oneweredig versprei. Natuurlike waterarm gebiede (woestyne en halfwoestyne) beslaan ongeveer veertig persent van die landoppervlakte van die aarde en word bewoon deur 'n relatief groot persentasie van die wêreldbevolking, maar beskik oor slegs 'n klein gedeelte van die varswater in vergelyking met ander gebiede.

Konvensionele bronne van varswater in waterarm gebiede, soos oppervlaktewater in riviere, mere en damme, is dikwels seisoenaal, en slegs beskikbaar gedurende die reënseisoen. Verder beland slegs 'n klein gedeelte van die reënval (0 – 5%) in die ondergrondse waterreserwes, en selfs hierdie grondwater vertoon 'n hoë mate van versouting, sodat die eindproduk te brak is vir menslike gebruik. Die swak gehalte van grondwater in waterarm gebiede word algemeen verstaan, maar daar is tot nog toe aanvaar dat dit oor die algemeen slegs 'n probleem is in gebiede waar oppervlaktewater nie voorkom nie. Hierdie studie ondersoek seisoenale grondwaterverbraking in seisoenale rivierbronne in sekere dele van Namibië en beoog om 'n beter begrip te formuleer van die aard van die probleem en hoe dit die inwoners van hierdie gebiede raak. Daar word ook ondersoek ingestel na moontlike oplossings vir die probleem, met die doel om 'n inligtingsbron vir waterbestuurders en wetenskaplikes wat verantwoordelik is vir die formuleer van oplossings vir watervoorsiening in waterarm gebiede daar te stel.

Hierdie oplossings is ontwerp om voordeel te trek uit die beskikbare geleenthede in die ondersoekgebiede, naamlik; die oorvloedige beskikbaarheid van sonenergie, alternatiewe bronne van varswater soos mis (Eng. "fog") en atmosferiese vog in die algemeen en aanpassings (Eng. "adaptations") vir die opvang van water wat voorkom by diere, veral insekte, in hierdie gebiede. Die resultate toon dat grondwater in die vlak seisoenale rivierbronne van die Namibwoestyn en die Cuvelai-delta in noord-sentraal Namibië hoë seisoenale variasie in totale opgeloste stowwe (TVS) en chemiese samestelling vertoon. Die laagste TVS-waardes word waargeneem tydens die reënseisoen, hoofsaaklik na die eerste reën in die hoë-reënvalgebiede en eers na vloede in die lae-reënvalgebiede. Die soutgehalte van die grondwater neem toe gedurende die res van die jaar en in die meeste gevalle verbrak die water tot ondrinkbare vlakke.

Die ondersoek na moontlike oplossings dui aan dat kleinskaalse fotovoltaiësgedrewe tru-osmose, sondistillasie en die opvang van mis (Eng. "fog collection") aangewend kan word om die seisoenale tekort aan drinkwater in hierdie gebiede aan te spreek. Die laedruk (6 bar) tru-osmose-ontsoutingseksperimente wys dat dit moontlik is om die eenheid met behulp van 'n sonkragedrewe pomp te bedryf en voldoende water te lewer vir die tipiese daaglikse drinkwaterbehoefte van 'n nedersetting in die Namibwoestyn. Hierdie eenheid sal sowat 4600 liter per dag (l/d) water, met 'n TVS-waarde van 500 mg/l, lewer. Dit is aansienlik meer as die lewering van soortgelyke eenhede in Australië en die Kanariese Eilande.

Die resultate wys ook dat die koste van sondistillasie-eenhede genoegsaam verminder kan word om dit 'n lewensvatbare opsie vir watervoorsiening aan enkelhuishoudings

in die plattelandse gebiede te maak. Die studie het ook bevind dat die opvang van mis 'n toepaslike alternatiewe bron van varswater is in sekere van die studiegebiede. Die miswater is oor die algemeen 'A'-gehalte drinkwater volgens die Namibiese gehalteriglyne vir drinkwater (gebaseer op bepalinge van die Wêreldgesondheidsorganisasie) en dat dit net so, of vermeng met brak grondwater, gebruik kan word as drinkwater. Vermenging is besonder geskik in die sentrale Namibwoestyn, aangesien die periode van hoë grondwaterverbraking saamval met die piek van benutbare misneerslag.

Die resultate toon ook aan dat miswater opgevang kan word met verskeie tipes polimeriese skadunet, wat maklik verkrygbaar is, en verskaf riglyne vir die optimale skadu-koëffisiënt en weefpatroon van moontlike misvangsnette vir voornemende gebruikers van misvangstechnologie in gebiede waar die polipropileenet wat in die standaard miskollekteerders gebruik word nie, beskikbaar is nie. Die ondersoek van oppervlakeienskappe van mis-koesterkewers (Eng. "fog harvesting beetles") en eksperimente met verskeie prototipe versamelaars toon dat dit moontlik is om die waterproduksie van bestaande kollekteerders te verhoog. Die hidrofobe oppervlaktetoestande soos gevind op die opperhuid van die mis-koesterkewers (*Onymacris unguicularis* en *Onymacris bicolor*) bevorder die vorming en afloop van groot misdruppels op die versameloppervlak.

Die prototipe suigwaaier- en verkoelerstelselgebaseerde versamelaars toon dat dit moontlik is om die misvogversameling op polimeriese nette tot drie maal te verhoog en dat 'n vergelykbare volume atmosferiese vog versamel kan word, selfs in die afwesigheid van mis, tot by 'n relatiewe humiditeit van ongeveer 40%.

Ten slotte benadruk die studie dat grondwatersoutgehalte in waterarm gebiede soms 'n seisoenale probleem is, en dat dit in ag geneem moet word in watervoorsieningstrategieë vir sulke gebiede. Dit benadruk ook dat atmosferiese vog 'n bruikbare alternatiewe bron van varswater kan wees in sekere areas, waar dit dikwels verskeie male meer is as reënval, en gesien behoort te word as 'n belangrike aspek in strategieë om waterprobleme in hierdie gebiede aan te spreek. Die studie beveel sterk aan dat wetenskaplikes, ingenieurs en waterbestuurders in hierdie gebiede altyd die beskikbare geleenthede soos klimaatstoestande (bv. misneerslag) en aanpassings vir vogvangs/bewaring wat voorkom by inheemse plante en diere sal navors om sodoende onderhoudbare oplossings vir die probleem te vind. Hulle behoort deurlopend op hoogte te bly met ontwikkelings/geleenthede wat ontstaan in die wyer waterindustrie, wat van waarde kan wees in by waterverskaffingsinisiatiewe vir afgeleë gebiede in ontwikkelende lande.

Laastens dien die studie om 'n beter begrip daar te stel van die aard van grondwatersoutvlakke in waterarm gebiede wat afhanklik is van seisoenale oppervlaktevloei vir watervoorsiening sowel as om 'n bydrae te lewer tot die formuleer van oplossings tot die probleem in hierdie gebiede, veral in die hiperdroë omgewings aan die Namibiese weskus, waar konvensionele waterbronne mees onvoldoende is. Dit benadruk ook die rol van materiaalkundige wetenskappe (polimere) en omgewingsingenieurswese sowel as die UNESCO-geassosieerde wetenskaplike instellings in die formulering van volhoubare oplossings vir sommige van die huidige waterprobleme in waterarm gebiede.

Sleutelwoorde: *Waterarm gebiede, hidrochemie, bronne van varswater, ontsouting, atmosferiese vog*

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LIST OF ABBREVIATIONS

BWRO	Brackish Water Reverse Osmosis
DCA	Dynamic Contact Angle Analyser
EC	Electrical Conductivity
ED	Electrodialysis
EDX	Energy Dispersal X-ray
HDPE	High-Density Polyethylene
IDA	International Desalination Association
l/m ²	Litres per square metre
mg/l	Milligrams per litre
MSF	Multi-stage Flash distillation
MVC	Mechanical Vapour Compression
MWD	<i>Grahamtek</i> Mineral Water Development (Company)
psi	Pounds per square inch
PV	photovoltaic
PVC	polyvinylchloride
RO	Reverse osmosis
SFC	'Standard Fog Collector'
SWRO	Sea Water Reverse Osmosis
TDS	Total Dissolved Solids
TVC	Thermal Vapour Compression
u-PVC	unplasticised-polyvinylchloride

CHAPTER 1: INTRODUCTION & OBJECTIVES

1.1 Introduction

Freshwater is the most fundamental of all life-supporting resources that determine our social, economic and political wellbeing. It is, however, only a small percentage of the world's water resources and is also unevenly distributed. Arid regions make-up about forty percent of the world land area and have a larger proportion of the world population, however, they only have a small fraction of the freshwater compared to other areas (Waddel & Maxwell, 1998; AAAS, 2000; Kiel & Kayne, 2001 and Pigram, 2001).

Groundwater in arid environments is also often too saline for human consumption, particularly in remote rural locations where the water supply infrastructure is not well developed. This aspect of water in arid regions has been a subject of international investigation, however, an important aspect of this problem is largely overlooked (Agnew & Anderson, 1992; Richter & Kreitler 1993; Whitehead et al., 1985 and Waddel et al., 1988). This study looks at groundwater salinisation and possible solutions to this problem in arid regions where the water sources are dependent on recharge by seasonal floods. Groundwater quality deterioration in these sources is of major importance to understanding the water situation in arid regions because most people in these areas are directly dependent on this kind of water sources for water supply and are therefore subject to a seasonal shortage of potable water.

The current global trends such as the population growth and changing environmental conditions e.g. global warming, are also most unfavourable in arid regions and present an even greater challenge for the development, management and use of the water resources in these areas (UN Agenda 21, 1992; AAAS, 2000; Matsuura, 2000; Vorosmaty et al. 2000 and AEO, 2001).

These trends are a well-recognised source of problems that threaten the social, economic and political stability in arid regions. Indeed, a number of authors indicate that water, more than any other resource, is likely to become the dominant limiting resource and primary cause of conflicts of the 21 Century (Matsuura, 2000 and Pigram, 2001). There is therefore a strong global consensus and inclination to support the development of freshwater options, particularly in remote rural areas in developing countries where aridity has more severe socio-economic consequences than in richer urban areas that can afford expensive solutions (UN Agenda 21, 1992; GWP, 2000 and Kiel & Kayne 2001).

This study aims to contribute to the efforts to improve access to potable water in remote communities of the Namib Desert and parts of North central Namibia. It joins other international efforts such as in Botswana, The Canary Islands, Greece and Western Australia to investigate possible solutions for remote settlements in arid areas (Yates et al., 1998; Herold et al., 2000; Goen Ho, 2001 and Mathew et al., (001) by: *exploring some of the recent advances in membrane technology and desalination to develop non-conventional sources of freshwater technology and strategies, and also to improve the general understanding of collection of alternative sources of freshwater in arid environments.*

1.2 Objectives

The overall aim of this study was to improve the understanding of arid land groundwater salinity and also to contribute to the development and conjunctive use of non-conventional water sources in these areas. The study explores some of the recent developments in polymeric membrane technology for desalination to develop small-scale solutions for water supply to remote communities in arid regions. It also aims to improve the understanding of collection of atmospheric moisture through investigations with various prototype fog collectors and by incorporating aspects of naturally occurring opportunities such as animal adaptations, into atmospheric moisture collectors in order to increase their productivity and efficiency. The following were the specific objectives of the study;

- ☐ Determine the seasonal variation in chemistry of ephemeral river groundwater sources;
- ☐ Investigate the feasibility of solar-powered reverse osmosis with a polyamide membrane unit to see if it is cost-effective for water supply in remote rural areas;
- ☐ Construct and test cheap solar distillation units using various types of framing & insulation material in order to lower the cost of solar distillation units to enable use in rural communities;
- ☐ Assess the quality of fog water in the Namib Desert to see if it is of good drinking quality;
- ☐ Analyse surface properties such as surface contouring by Scanning Electron Microscopy (SEM) and contact angles (hydrophilic & hydrophobic surface conditions) of fog harvesting animals to see if they have properties that can be used to increase fog collection in man-made fog collectors;

- ❑ Construct and test prototype fog collectors, both passive and active, (cooling system and extractor-fan based collectors) to improve the understanding of fog collection that could enable design of efficient fog collectors;
- ❑ Investigate the feasibility of using other polymeric meshes such as cheap and freely available greenhouse shade netting, in fog collectors;

1.3 Outline of the report

The report is structured in the following order:

Chapter one is an introduction to the study and serves to introduce the problem that this study seeks to contribute to addressing. This chapter also discusses the objectives of the study.

Chapter two presents the general methodology that was adopted for the study. The detailed methods are given in each publication. **Chapter three** is a literature review on historic attempts to address the water problem in arid regions as well as the current trends in membrane technology and desalination.

Chapters four to six contain the publications that emanated from this work. **Chapter 4** is the publication on the hydrochemistry of the study areas and serves to define the problem that the thesis aims to address. **Chapter 5** presents findings of investigations of small-scale solar desalination as a possible solution to the problem while **Chapter 6** presents the findings on fog collection. This chapter discusses the climatology of Namib fog and how it relates to groundwater salinisation and the current fog research in the Namib.

It also presents the investigations of adaptations for fog collection in beetles that are found in this area as well as results of experiments with various prototype fog collectors that were conducted in order to contribute to the general understanding of fog collection technology.

Chapter 7 summarises the discussion and conclusions of the research findings of this study from the publications that are presented in the preceding chapters.

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CHAPTER 2: METHODOLOGY

2.1 Introduction

The study was organised in the following order; problem definition (groundwater salinisation in ephemeral river basins in arid environments); a literature review of solutions to this problem; investigation of possible solutions that occur in nature such as fog collection in desert animals and lastly, to investigate and also design model freshwater supply technology that would contribute to new knowledge and insight on the use of supplementary sources of freshwater in arid environments.

The approach of this study was based on a background in environmental engineering and chemistry. In short, by an understanding that frequently, nature presents valuable opportunities that can be implemented to address some of our current problems, for instance, that adaptations that occur in species that inhabit water deficient areas such as desert environments could contribute knowledge to mankind's effort to design solutions to resolve water problems in these areas. This is particularly so because the smaller species have shorter life-spans and therefore a higher rate of re-generation and as a result, it requires much shorter time-spans for them than in larger and slower breeding species such as humans, to develop adaptations to existing environmental pressures (see Chapter 6 for references). The acquired adaptations therefore also evolve a lot faster towards more advanced states in these species.

In conclusion, the study sought to explore some of these naturally occurring opportunities in these water deficient environments to address the problem. It combines environmental engineering and materials sciences to investigate alternative sources of freshwater for people in arid environments.

2.2 Methods

This chapter provides a summary of the thesis methodology, particularly the fieldwork that was conducted by the candidate during the course of this study, Figure 2.1. The specific methods that were used are also presented in each publication.

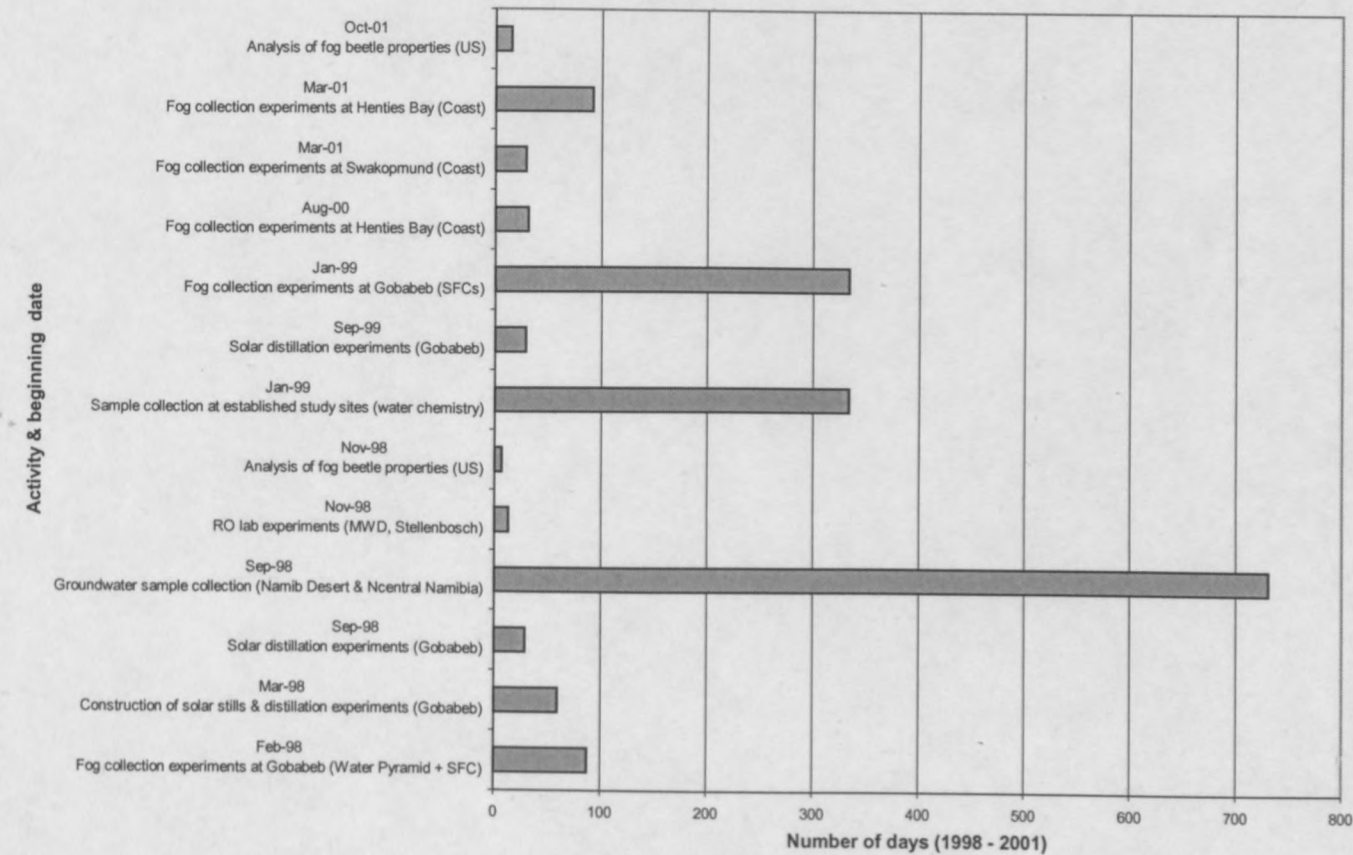


Figure 2.1 A summarised time-line of the fieldwork conducted for this study.

2.2.1 Hydrochemistry

2.2.1.1. Fieldwork (data collection)

The earlier work of the study concentrated on collection of water samples from drinking water sources in the Namib Desert and North central Namibia in order to determine the seasonal variation of water quality in these areas, Figure 2.2.

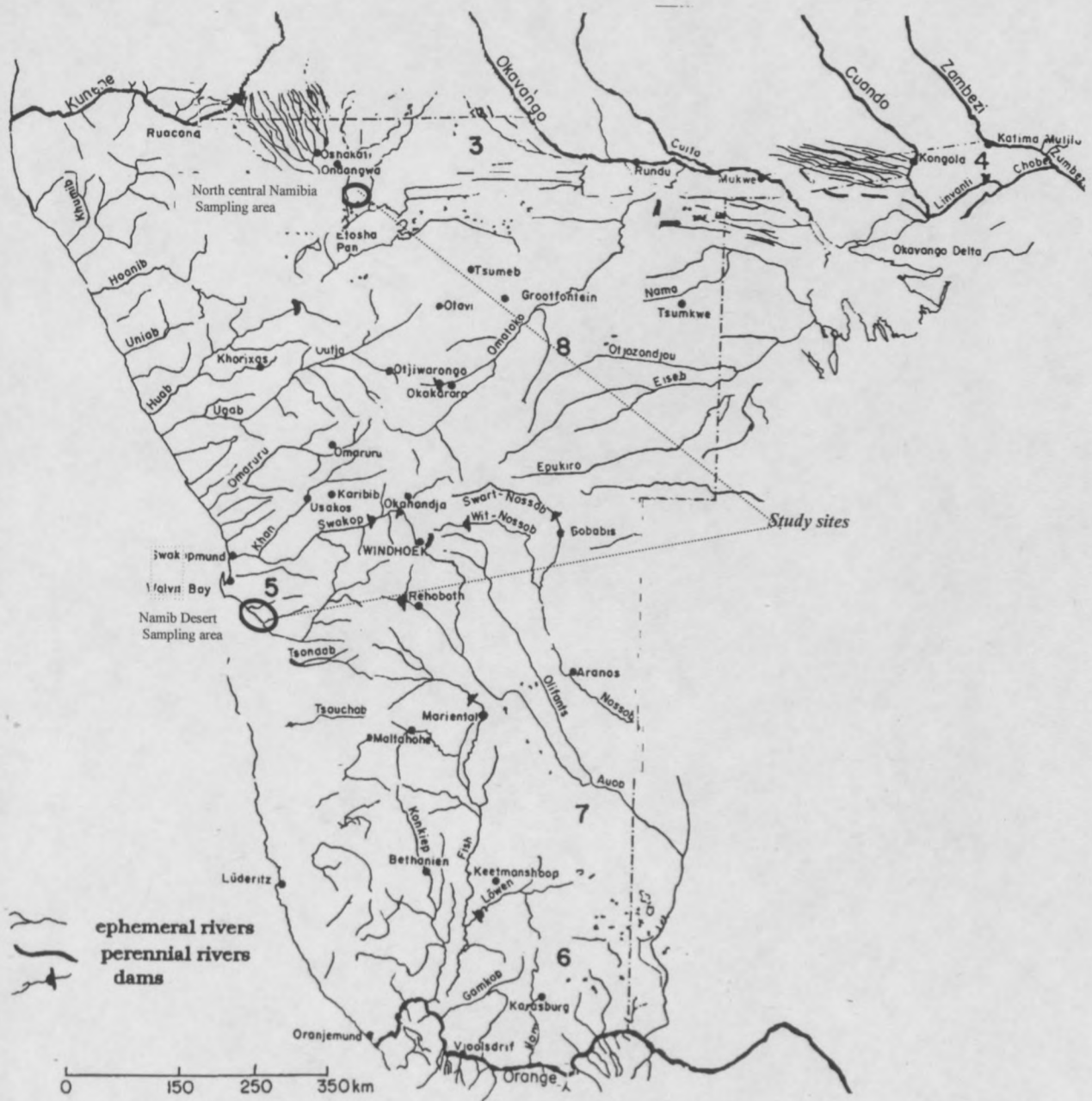


Figure 2.2. Perennial (bold-lines) and ephemeral rivers in Namibia (source: Ward, 1994- Chapter 4).

These study sites were chosen because they represent the typical water sources, namely the ephemeral river-based groundwater sources, which are used for water supply to most of the rural areas in the country. Sampling at the field sites was conducted by the PhD candidate, however, it was later arranged such that the local residents collected water samples from their wells and boreholes on a monthly basis, which was then picked up on occasion. The water samples were all collected within the period from September 1998 to September 2000. A good number of water samples were collected, however, only about 80 of them were used for the study. The remainder were left out of the study because they had ion balances that were much higher than one, which would indicate a sampling error or contamination. However, the remaining data set was still sufficient to investigate the seasonal variation of water quality in some of the water sources in both study sites.

Water samples were obtained from shallow boreholes and wells (water level 10 - 23 meters) at the ROSSING Okashana Training Centre and three neighbouring villages in north central Namibia which are located about 25 kilometres from the Etosha National Park, and were all within a radius of about 10 kilometres (detailed maps for this area are not available). Samples were also obtained from boreholes at Homeb (± 75 km from the sea), Natab 2 (± 65 km), Natab 1 (± 60 km) and Gobabeb (56km) in the Namib Desert.

2.2.1.2. Chemical analyses

The samples were analysed for major ions, TDS and electrical conductivity (EC) at the NAMWATER laboratories in Windhoek, Namibia, and at INFRUITEC, in Stellenbosch, South Africa. The major ions were determined by atomic absorption spectroscopy, using direct flame and with a Skalar San Plus automatic analyser calibrated to generally accepted method. TDS was determined by evaporating the sample and drying it at 180° C while EC was measured with a Crison Micro CN 2200 electrode.

2.2.2. Solar desalination

2.2.2.1. *Solar distillation units*

The investigations of possible solutions to water problems in the study areas dealt with small-scale solar desalination and fog collection. Solar distillation units (solar stills) were constructed with various materials at the Gobabeb Training and Research Centre (GTRC) and the preliminary investigations were conducted at the beginning of 1998, Figure 2.3.



Figure 2.3. Construction of solar stills at Gobabeb and some of the initial trials with the different units.

The solar stills were constructed according to the specifications of McCracken and Gordes (1985) {see desalination publication in chapter 5 for reference} with deviations from some of the proposed materials such as the galvanised steel bottom covering and aluminium frames {see solar desalination publication for references} in order to reduce the cost of producing such units and through that, their cost of water production and also to make them affordable to rural communities in the Namib Desert. The stills had surface areas of about 1.6 m² and were made with polyvinylchloride (PVC) and un-plasticised polyvinylchloride (u-PVC) window framing that was obtained from NAMIB WINDOWS Pty. Ltd., in Swakopmund and with fibreglass. The insulation was made from polyurethane, expanded polystyrene and cotton wool. Silicone sealants were used to waterproof the stills. Some of the construction methods I learnt while working with Ian Goldie and his solar distillation project of the South African Water Research Commission (WRC), at the Division of Polymer Science, University of Stellenbosch. These lessons I then applied in building the above solar stills with local Namibian materials.

2.2.2.2. Reverse osmosis

Laboratory experiments were conducted with a small reverse osmosis (RO) unit in November 1998 at the laboratories of *GrahamTek* Mineral Water Development in Stellenbosch, Figure 2.4.



Figure 2.4. The polyamide membrane reverse osmosis unit that was used for the experiments.

This unit has a polyamide spiral-wound membrane and it is operated on a 220-volt power supply. The experiments were designed and carried out over a few days in order to investigate the feasibility of desalinating saline groundwater at an operating pressure that can be delivered by a Photovoltaic-operated pump. An operating pressure of 6 bar was chosen because the most appropriate pumps have a maximum operating pressure of between 6.2 - 6.9 bar.

Sea salt was added to the feed water in order to steadily increase the total dissolved solids (TDS) from about 4000 mg/l to 13000 mg/l which are the typical TDS values encountered in the Namib and north central Namibian water sources, particularly during the dry season. The following parameters were then recorded; the TDS of feed water and product water, and the flow rate of the product water (yield) and that of the reject water.

These measurements were then used to estimate the performance of the photovoltaic-operated unit and also to compare it to similar small-scale RO desalination units that are being used in other parts of the world. Information on other small scale RO units was acquired through literature reviews and contact with leading desalination institutions such as the Rabin Desalination Laboratory and Water Research Institute in Egypt, through their Director (Dr. Raphael Semiat) as well as other sources such as the creators of the World Wide Water website (Mr & Mrs. John and Jodie Toner). The actual implementation, that is, assembly of the PV-operated MWD unit and field testing in the Namib Desert was planned for 1999, however, this was postponed by the developer, and is only planned to happen sometime during this year (2002).

No attempt was made to simulate natural saline water with regard to other ions such as Calcium, Magnesium, Sulphates and other fouling agents. The reliability of this desalination unit will therefore depend on the results of field trials.

2.2.3. Techniques used for fog collection

The experiments on fog collection were conducted with fog basking beetles, single-strand polypropylene fibres that were roughened to various extents using sand papers of different roughness and for different times, polypropylene polymeric greenhouse shade nets that are used in standard fog collectors (SFC), other greenhouse shade nets and with a cooling system and also an extractor-fan based collector. These experiments were conducted in order to establish a better understanding of fog collection that could contribute to development of efficient fog collectors and also to investigate the use of other polymeric materials, particularly readily-available shade nets, for fog collection.

2.2.3.1. Natural fog harvesters

Several fog harvesting beetles of the species *Onymacris unguicularis* (± 30 beetles) and *Onymacris bicolor* (10 beetles) were collected in the central and northern parts of the Namib Desert between 1998 and 2001. These beetles were mounted on wires that were looped in beakers at an angle of about 35 degrees and were then put outside for fog collection during fog events, Figure 2.5.



Figure 2.5. Fog collection experiments with fog basking beetles in the Namib Desert.

The 35-Degree of inclination was determined by measurements that were done on pictures taken of these beetles during fog basking.

Several of these experiments were conducted inland at Gobabeb as well as at Henties Bay and Mowe Bay, along the coast, however, neither of the experiments yielded measurable volumes and as a result, it was necessary to look instead at fog collection in fibres that were grated with sand paper at varying degrees in order to determine the ideal surface properties, i.e., hydrophobic or hydrophilic surface conditions, Figure 2.6.



Figure 2.6. Fog collection experiments with new polypropylene fibres and ones that were grated to four different levels with commercially available sandpaper, *Corondrum 100, 80, 60* and *40*.

The results of these experiments were equally unreliable because the fibres did tend to vibrate in the fog-bearing wind, even in cases where the wind speed approaches zero. This was realised during continuous monitoring of the experiments during fog events and also by the fact that the results did not show any correlation with the level of grating but instead with their positioning.

An attempt was also made to increase the number of fibres that were mounted per set such that the experimentals are positioned in the middle of the set and thus shielded away from the wind by a lot of spare fibres. However, even this set-up did not produce meaningful results because the wind effect remained. It is therefore recommended that future studies should use other means, preferably whole fog nets that are treated mechanically or chemically (e.g. with greasing and degreasing solutions) in order to vary their surface properties.

This option was not available in Namibia and could therefore not be implemented and as a result, the study focused mainly on interpretation of the results of the contact angle measurements that were done with the DCA contact angle analyzer.

2.2.3.2. Polymeric greenhouse shade nets

Fog collectors were made from polymeric greenhouse shade nets that are available in Southern Africa as well as with the standard material that is used for construction of fog collectors elsewhere, in order to investigate the feasibility of using locally available greenhouse shade nets in fog collectors.

About 30 fog collectors were made from the polypropylene mesh (Rachel mesh) that is used in standard fog collectors (SFC) as well as with high density polyethylene “Aluminet” greenhouse shade nets of different percent shade coefficients (40%, 60% and 90%) and two weaves namely the indoor and outdoor weaves, Figure 2.7. and Figure 6.4.1.

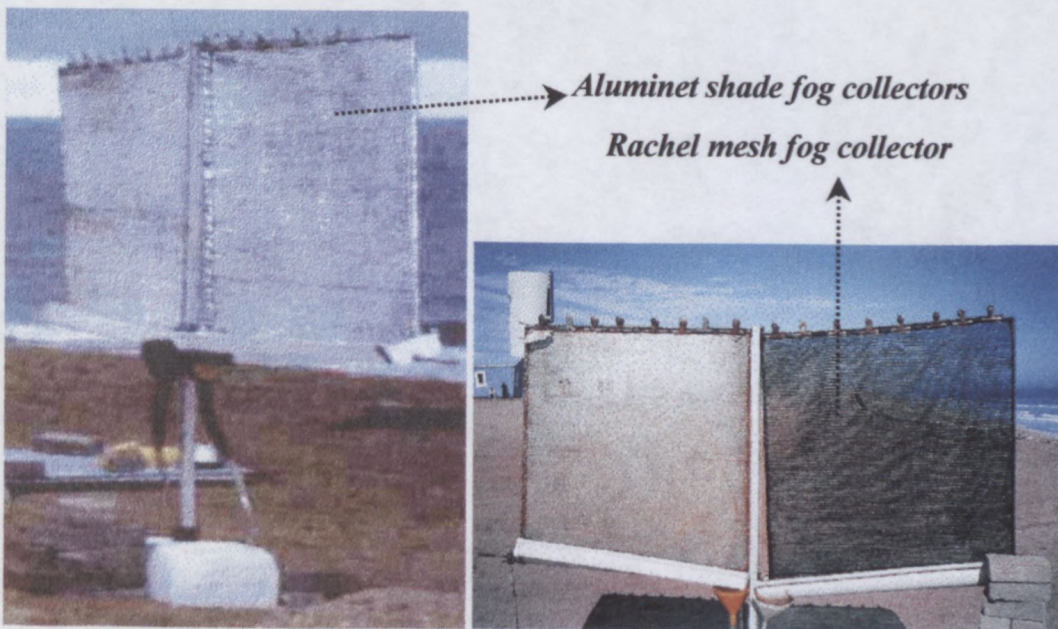


Figure 2.7. Some of the fog collectors that were made from the Rachel mesh and Aluminet greenhouse shade nets.

The Rachel mesh was acquired from the International Development Research Centre (IDRC Canada) through the Desert Research Foundation while the “Aluminet” shade net was acquired from Aluminet South Africa, a company in the western Cape, Republic of South Africa. The material was cut into to 2 x 1 metre pieces which were then folded into a 1 m² sheet that was sown at all four ends to make the 1 m² fog screens that were used for the experiments, Figure 2.8. These fog collectors were erected in the Namib Desert at Gobabeb, however, similar portable units were also constructed so that experiments could be carried out anywhere else while travelling between field sites. Additional data was also obtained from SFCs that were erected in 1997 by the DRFN at a number of villages in the Namib Desert

In all the experiments, the new collectors were operated alongside an SFC so that even when the experiments were only conducted for a few days or weeks, the results could still be related to the SFC whose long-term records already exist for the Namib and other areas around the world where fog collection is being investigated.

1.2.3.3. Alternative fog collectors

Fog collection experiments were also done with other alternatives to the greenhouse shade nets that are used in SFCs. These include collectors where an extractor fan is used to draw fog through the net, Figure 2.8; the Norwegian Water Pyramid, Figure 2.9 and a cooling system collector where the fog is intercepted by a cooled surface, Figure 2.10.

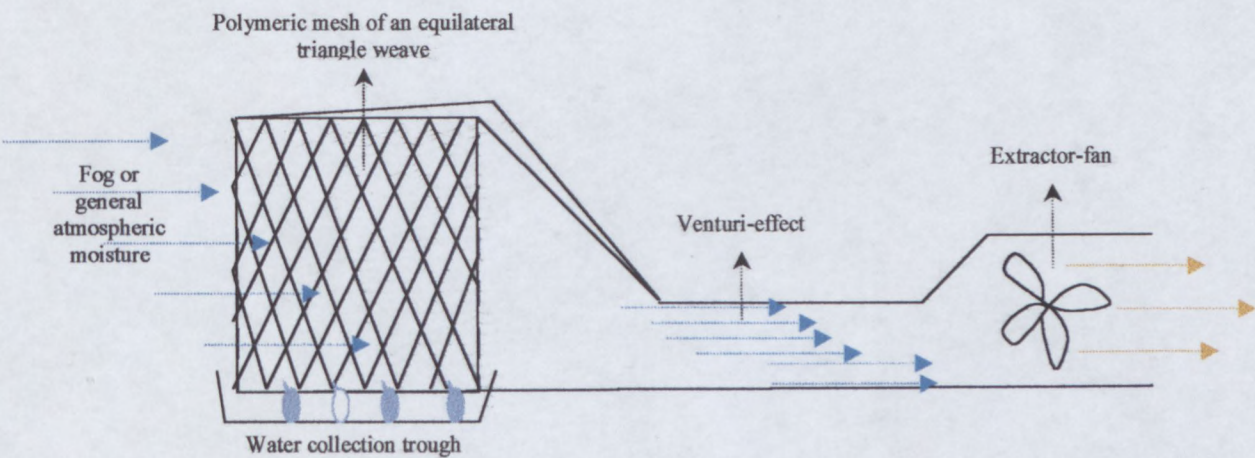


Figure 2.8 A schematic view of the extractor-fan fog collector that was developed for this study

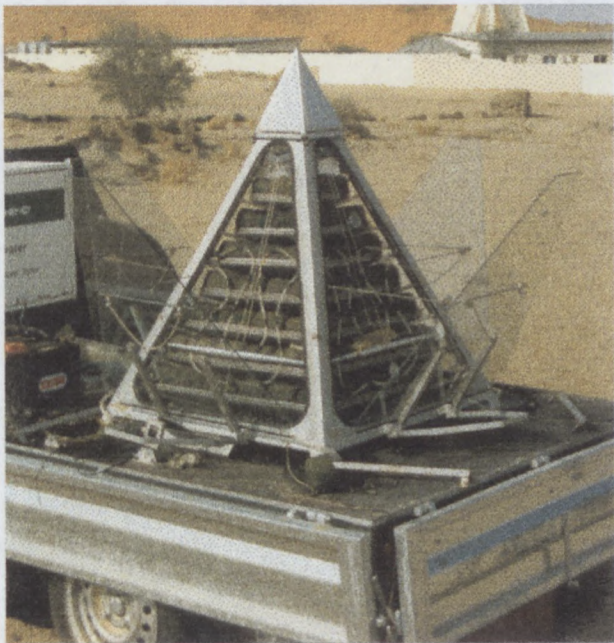


Figure 2.9. The Norwegian Water Pyramid developed by Krupec Inc. in Norway.

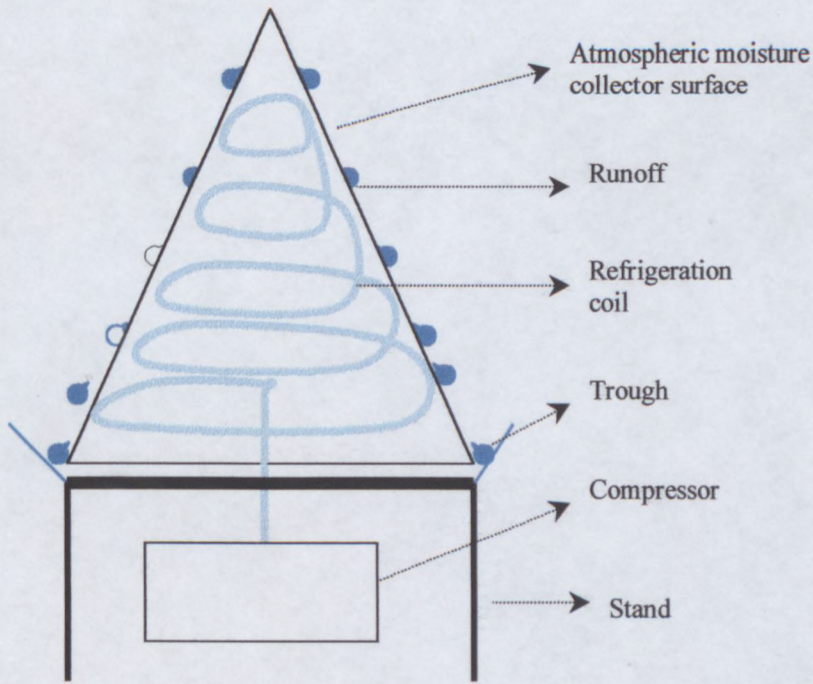


Figure 2.10. A schematic view of the cooling system fog collector that was developed for this study.

The extractor fan collector was constructed after initial experiments that were conducted with a polymeric mesh that was mounted on a moving vehicle indicated that the amount of fog water that was collected by the collector was dependent on the speed at which fog passes through it. This effect was later incorporated into the polymeric fog collector by attaching an extractor fan (Donkin series: MAJAX-2, 1440 r/min and FREQ. 50 Hz) to an airtight housing that had the collector attached at the entrance, Figure 2.9. This system is able to induce airflow of about 10 m/s over the surface of the collector. Further experiments were planned to investigate the effect of varying the airflow, however, these were not possible due to technical problems that were encountered.

The Water Pyramid consists of shredded paper that is packed inside a glass compartment, Figure 2.10. This unit is opened during the evening in order to allow for absorption of atmospheric moisture onto the shredded paper fibres. It is then closed in the early morning hours so that it heats up and the absorbed moisture evaporates on the inner side of the glass cover from where it is directed to a storage compartment. According to the inventor, the unit is priced at about ZAR 30, 000.

The cooling system was developed during this study in order to investigate the effect of using a cooled collector surface on fog and general atmospheric collection. This unit was made from a small refrigeration compressor unit that is mounted with a coil that lines the interior of the covering glass compartment- the collecting surface, Figure 2.11. The compressor is able to cool the interior of the collector to about -10 °C. The fog water is collected on the outside of the cooled glass cover. The cost of construction was about ZAR 2000.

2.2.4. *Quality of fog water*

This aspect of the study was motivated by the fact that no other study has looked at the quality of fog water that is collected by the polymeric fog collectors. All the earlier studies such as Eckardt and Schemenauer, 1998, used other collectors where the fog water is sampled directly into a chemical analyser. It was therefore necessary to determine the quality of fog water that would be supplied to the users of fog water supply schemes in the Namib.

A total of 8 samples were collected at Gobabeb, which is close to the rural areas where fog collection schemes are envisaged, and sampling was done between March 2001 and May 2001 because this is the period during which dust storms are more prevalent in the Namib Desert. The samples were analysed for major ions, TDS and EC at the NAMWATER laboratories by similar methods as those used for the groundwater analysis (section 2.2.1.2).

CHAPTER 3: BACKGROUND

3.1 Investigations of alternative sources of freshwater in Desert environments

3.1.1 Freshwater Resources in Desert environments: geographic description

Deserts are found in the region between 15 and 35 degrees latitude, over the Tropics of Cancer and Capricorn, Figure 3.1 (Walton, 1971 and Petrov, 1976). They generally occur due to the following factors;

Continental deserts: due to their remoteness from sources of moisture;

Rain shadow: on the leeward sides of high mountains because most of the moisture precipitates on the windward side, and;

Coastal: on the west coast of continents along cold ocean currents and anticyclones that, together, give rise to a temperature inversion that inhibits cloud development and precipitation.

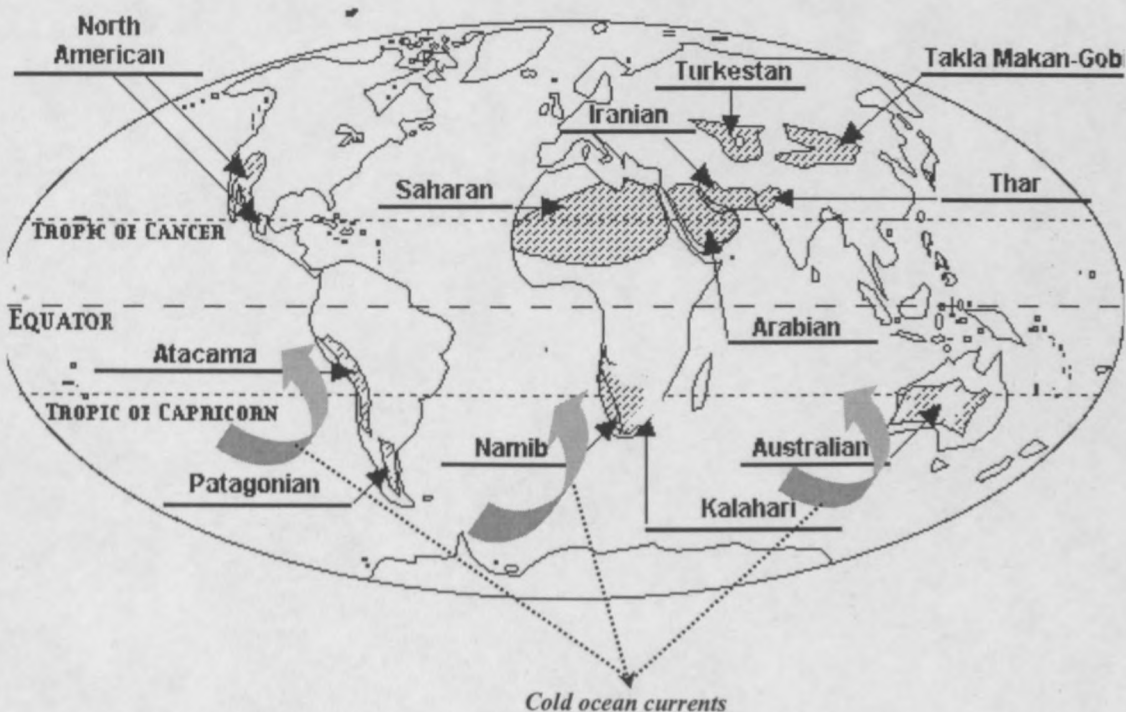


Figure 3.1. World distribution of Deserts and cold ocean currents (Source: Amiran & Wilson, 1973; Petrov, 1976; Agnew & Anderson, 1992 and Nicholson, 1994)

Deserts are generally characterised by little and unpredictable rainfall (less than 250 mm/year) as well as high solar radiation. The most arid of these environments are the west coast deserts such as the Namib and the Atacama where annual rainfall approaches zero due to the effect of adjacent cold ocean currents that inhibit the formation of rain clouds (Walton, 1971; Amiran, 1973; Petrov, 1976 and Nicholson, 1994).

Conventional freshwater sources in arid environments are minimal and also highly variable in quality and quantity (Walton, 1971; Whitehead et al., 1985; Agnew and Anderson, 1992 and Gleick, 1999). An image of the world distribution of freshwater, Figure 3.2 shows that only a small percent of the world's water resources is freshwater. Most of this water is found in humid climates as opposed to desert environments (Agnew and Anderson, 1992; Uitto, 1997; and Gleick, 1999).

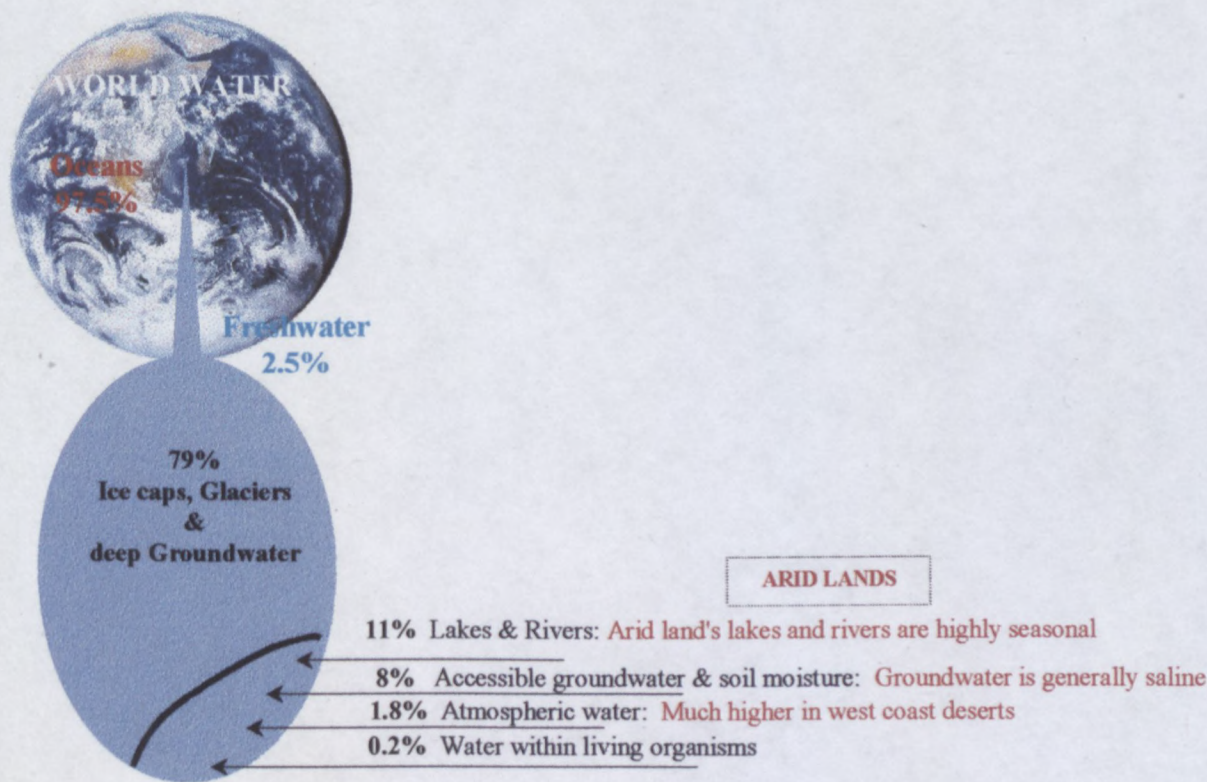


Figure 3.2. World distribution of freshwater (Source: Gleick, 1999; AAAS, 2000; AEO, 2001 and Pigram 2001).

Surface water in rivers, lakes and dams that are found in arid areas is often seasonal, available mainly during the wet season. Equally, only a small part of the rain (0 - 5% of rainfall) infiltrates into groundwater reserves, and even this groundwater displays high rates of salinisation such that the end-water is too saline for human consumption (Walton, 1971; Whitehead, 1985; Richter and Kreitler, 1993; Jacks and Rajagopalan, 1996 and Shanyengana, 1997).

This poor access to potable water in arid regions has been a source of social, economic and political difficulties over centuries as well as a subject of ingenious technological innovations to harness alternative water sources and to use the few resources conservatively (Baladon, 1995; Gioda et al., 1995; Birkett, 1999; Matsuura, 2000 and More, 2001). Civilisations that flourished in these regions did so mainly based on their ability to secure freshwater sources either through martial superiority over others or technological advancement (Birkett, 1999; Matsuura, 2000 and More, 2001). Some of these old age technologies are still applied in places and are a valuable source of lessons to water scientists and engineers in the search for water supply options for people in these regions.

3.1.2 Water investigations in desert environments: traditional wisdom

The water situation in arid lands has been a key issue at international conferences and in programmes such as the *United Nations Conference on Environment and Development* (Agenda 21) held in Rio in 1992; *The UNESCO Arid Land Programmes*, *The International Conference on Water and Environment* (ICWE) held in Dublin in 1992 and the *International Conference on an Agenda of Science for Environment and Development into the Twenty-first Century* (ASCEND 21). All these advocate an integrated approach to the development, management and use of water resources with emphasise on water conservation and demand management.

These programmes also indicate that the development of alternative sources of freshwater as well as acquiring wisdom from past arid land civilisations and improvement of some of the old techniques are imperatives for water security and sustainable development in arid regions.

Some of the most successful traditional techniques include runoff farming in the Negev; the use of extensive underground channels, *Qanats*, to transport water from higher rainfall areas such as once practised in the Middle East, South America and parts of China; and collection of dew and general atmospheric moisture, for instance in Theodosia in the 1600s (Gioda et al., 1995; Uitto and Schneider, 1997; and Hall & Dietrich, 2000).

Fog deposition generally exceeds rainfall in west coast deserts and presents a reliable source of moisture for plants and animals in these arid environments (e.g. Lancaster et al., 1984; Pietruszka and Seely, 1985; Cereceda et al., 1996 and Henschel et al., 1998). The collection of fog water for drinking purposes in coastal desert areas has also long been practised by using tree plantations that are surfaced with plastic sheets or stones piled in circles to collect dew in fields e.g. in Cape Verde and the Canary Islands (Baladon, 1995). In other cases, fog collected by trees such as in the famous case of the Island of Hierro and its Garoe tree was either harvested directly off the tree or channelled to storage wells for later use (Gioda, 1995). Stonewalls were also constructed in ancient towns such as Theodosia, to intercept fog and enhance condensation of atmospheric moisture (Schemenauer and Cereceda, 1994; Baladon, 1995; Gioda, 1995 and Nikolayev 1996).

In other desert environments where sources of freshwater such as fog are not available the inhabitants made use of extensive underground channels to transport water from high rainfall mountainous sites to the more arid interior. These waterworks are particularly reflected in *Qanats* in the Middle East, also known as karez or foggara in some other areas such as South America and China (Uitto and Schneider, 1997).

Most of these old-age technologies are in most cases long abandoned, however, they are still a valuable source of water engineering know-how to water programmes in these areas today. One such recent project is the world's longest water transfer scheme- The Great Man-Made River Project (GMMR) in Libya.

The GMMR project is now partially complete and it is envisaged to transfer water through a continental aquifer from the middle of the Sahara to Libyan coastal cities (Uitto and Schneider, 1997; ABB GmbH, 2000; and Matsuura, 2000). This kind of project reflects the basic characteristics of water infrastructure and utilisation patterns in arid regions- long distance transfers and the use of water that was once recharged when these desert environments were more humid. Similar investigations continue to be carried-out in the Sahara and the Arabian Peninsula by UNESCO, FAO, and the Observatory of the Sahara and Sahel (OSS). These projects are all based on knowledge gained from the age old *Qanats* and are testimony to the merits of combining the old-age basic principles and wisdom with today's technology to meet the challenge of sustainable development of freshwater resources in arid environments.

3.2 Developments in water supply technology

3.2.1 Atmospheric moisture

There has been much international interest in the collection and use of atmospheric moisture, particularly fog, for water supply to people in arid environments (Schemenauer and Cereceda, 1992; Schemenauer and Cereceda, 1994; Cereceda et al., 1996; Henschel et al., 1998 and Olivier, 2001). The current fog water supply schemes generally consist of a series of 48 m² polymeric mesh ('fog screens').

These screens are made from a double layer of 35% shade coefficient polypropylene mesh and it requires several such set-ups to secure sufficient volumes of fog water to supply a village or small town such as in the case of Chungungo in Chile where about a hundred and fifty fog screens are used to collect water for a community of over 300 people, Figure 3.3.



Figure 3.3. The world-leading fog water supply scheme at El Tofo, Chile (Source: Schemenauer and Cereceda, 1992)

This water scheme is able to meet the water demand of the fishing town and provides a daily water supply of about 30 litres per person per day (Schemenauer and Cereceda, 1992 and Cereceda et al., 1996). Similar fog collection schemes are currently being implemented in areas such as Peru, Bangladesh and South Africa (Schemenauer and Cereceda, 1994; Cereceda et al., 1996 and Olivier, 2001).

3.2.1.2 Trends

Fog water supply schemes are now being implemented throughout the World, however, there has been very little, if any, advancement in the technology. This study therefore contributes to generating a better understanding of fog collection as well as explores opportunities on how best this technology could be improved and incorporated into current water supply schemes in these areas.

3.2.2 *Trends in membrane development and desalination technology*

3.2.2.1 *Membranes and reverse osmosis*

Desalination has been practised since the 14th century with some of the earlier steps being in sea vessels during voyages of exploration (Birkett, 1999). These small desalination units were, however, mainly simple and inefficient systems that produced water of questionable quality and it was not until the mid-1800s that more efficient large-scale desalination systems started appearing (Wagnick, 1998 and Birkett, 1999).

The late 1880s saw the development and use of multi-effect evaporators in areas such as Yemen, Mombasa and Malta as well as the development of other desalination techniques such as Mechanical and Thermal Vapour Compression (MVC & TVC) (Birkett, 1999). However, the major breakthrough only came in the 1950s with the design of Multi-Stage Flash distillation systems (MSF) by researchers at AQUACHEM in the United States and G&J Weir in Scotland (Leitner, 1994; Birkett, 1999 and Buros, 2001).

The MSF distillation units are arranged in a series of successive evaporation chambers, each at a lower pressure than the preceding one, which induces flashing of the liquid in each stage and therefore increases the overall productivity of the unit (Worthen and Barbour, 1952; Semiat, 2000 and Buros, 2001).

The 1950s also saw the development and use of membrane systems in Electrodialysis (ED) and Reverse osmosis (RO) desalination (Awerbuch, 1999 and Birkett, 1999). The RO systems took longer to commercialise than ED because it required a lot of research to develop membranes with satisfactory selectivity and throughput to make them practical. However, this delay was overcome in the early 80s.

RO has since then surpassed all other desalination systems except in the oil-rich Gulf States where MSF is still the dominant technology (Birkett, 1999; Meilke, 1999; Semiat, 2000 and Buros, 2001), Figure 3.4.

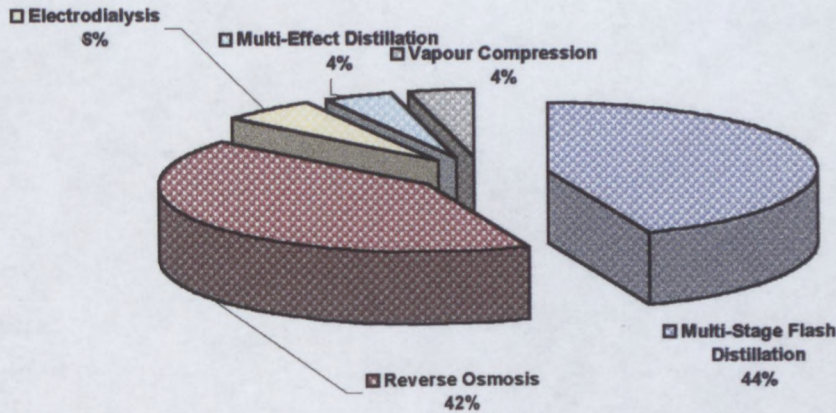


Figure 3.4. World installed capacity of desalination systems by process {Based on Semiat (2000) and Buros (2001)}

A lot of the improvements in RO desalination over the years occurred mainly due to the developments in membrane technology. Earlier RO membranes were made from simple cellulose acetate or related cellulose. However, these were later replaced with higher performance microporous polysulphones that are coated with a thin film of permeable polyamide (Semiat, 2000 and Buros, 2001).

Generally, the RO membrane films are currently made from polyamides, polyimides and polysulfones in two basic configurations. The first is a flat membrane sheet that is rolled with interleaved spacers around a flat membrane sheet, the *Spiral wound membrane*, while in the second approach, the membrane material is cast into fine hollow fibres, *hollow fibre membrane* (Belfort, 1993; Buros, 2001 and Paulson, 2001).

The spiral-wound membranes currently dominate in RO systems and their price continues to decline due to advancement in membrane technology and also because of the growing membrane industry and thus, competition (Owen et al., 1994; Leitner, 1999; Meilke, 1999; Semiat, 2000; Owens and Brunsdale, 2000 and Paulson, 2001). Figure 3.5 shows that the relative cost of spiral-wound membranes has declined by more than 60% since 1980 (Awerbuch, 1999; Semiat, 2000 and Buros, 2001).

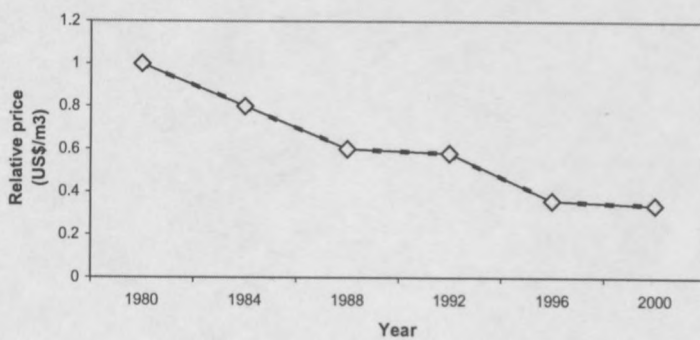


Figure 3.5. The trend in the cost of spiral-wound membrane modules.

The price reduction is also accompanied by an improvement in membrane performance such that water conversions of 90-95 percent can now be achieved in case of brackish water and about 35 - 50 percent recovery in seawater reverse osmosis systems (Awerbuch, 1999; Semiat, 2000 and Paulson, 2001).

The current Brackish Water RO (BWRO) systems operate at pressures ranging from 15 to 25 bar (ca. 225 to 375 psi) and at about 60 to 80 bar (800 to 1,180 psi) for seawater desalination (Awerbuch, 1999; Semiat, 2000 and Buros 2001).

The developments in membrane technology are also accompanied by other techniques to enhance the performance of these systems such that it is now forecast that RO systems would continue to dominate the desalination markets. This is particularly expected to happen in the form of hybrid systems where RO is combined with techniques such as Nanofiltration (Mulder, 1993; Meilke, 1999; Al-Sofi, 2000; Mourato, 2000; U.S. Patent, 2000 and Buros, 2001). Such hybrid systems would increase the overall performance of RO systems by reducing permeate salinity and scaling potential as well as the cost of water production due to the reduced energy consumption in these systems (Kunikane et al., 1994; Awerbuch, 1999 and Buros, 2001). RO is therefore one of the most rapidly advancing desalination techniques that has immense potential for application in small-scale remote area water treatment facilities (Med. conf., 2000 and Winter et al., 2001).

The implementation of the recent developments in RO technology into small scale desalination devices is still in its embryonic stage. The few field trials of some of the resulting prototype RO units, however, indicate better results than in current units (Childs and Dabiro, 1998 and Glueckstern, 1999). These developments and a number of other recent advances in desalination technology e.g. co-generation, the use of renewable energy as well as energy recovery equipment (special energy conversion turbines) have been key issues at international conferences on remote area desalination technology such as the ones held in Greece in 1998 and 2000 (Meilke, 1999 and Med. conf., 2000).

The actual implementation of most of these recent developments in small-scale remote area desalination schemes still lags behind developments in the larger desalination industry and requires updating and continuous re-adjustment in order to fully-integrate some of these advancements.

The use of renewable energies would particularly make desalination a more affordable alternative for rural communities in arid environments considering that energy consumption is the main component in the cost of desalination schemes, Figure 3.6 (Awerbuch, 1999; Glueckstern, 1999; Voivantas, 1999; Buros, 2001; Kalogirou, 2001 and Winter et al., 2001).

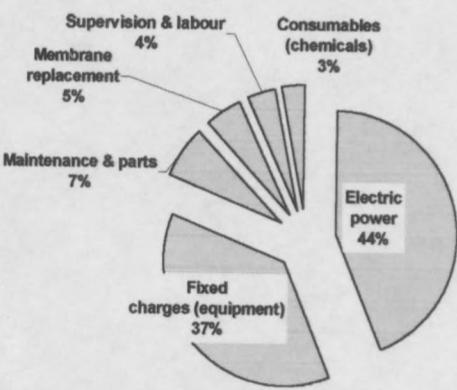


Figure 3.6. Typical Reverse osmosis system cost distribution (Source: Awerbuch, 1999).

The experiments in Australia and the Canary Islands indicate that Photovoltaics is one of the renewable energy options that can be used to reduce the operating cost of these systems and could thus induce the development/implementation of remote area RO systems in developing countries.

3.2.2.2 Solar distillation

Solar distillation has been known since the fourth century B.C., when Aristotle proposed it as a way to purify water for drinking purposes, however, it was not until the late 1800s that this technique was implemented for water supply to settlements such as in the case of Las Salinas, Chile in 1872 (Birkett, 1999 and Foster & Eby-Martin, 2000). Solar distillation makes use of the heat of the sun to heat water in a basin that is covered with a transparent cover, causing it to vaporise and condense on the inside of the cover from where it runs down into a collection trough, Figure 3.7.

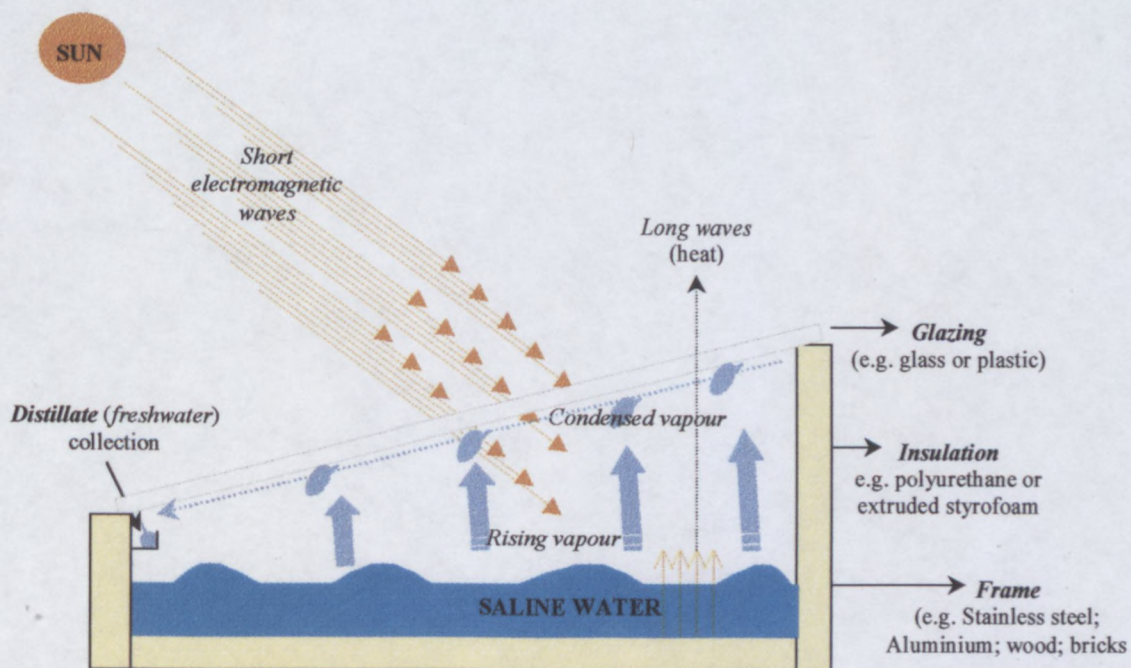


Figure 3.7. The principle of solar distillation

In principle, the short electromagnetic waves from the sun pass through the clear glazing and strike the darkened bottom surface and are then reflected back into the water medium as long waves (heat), heating the water and causing it to vaporise.

The vapour, ultimately the product water, leaves behind the salts and almost all other impurities, including micro-organisms, that are dissolved or suspended in the water because most of them vaporise at much higher temperatures than the 100°C that is required for water to vaporise (McCracken & Gordes, 1985 and Buros, 2001).

Interest in solar distillation units (also called flat-plate distillers or solar humidification units), however, did not pick up until the 1950s, following on the small stills that were constructed for use on life rafts during World War II (Birkett, 1999 and Buros, 2001).

The work on solar stills continued with some of the prominent examples being the experimental site at the Solar Distillation Station at Daytona Beach, Florida; and research and implementation of solar stills in some remote settlements in Mexico and Greece (Lof et al., 1961; Foster and Eby-Martin, 2000 and Buros, 2001). This work involved mainly deep basin stills and flat-plate solar still units, Figure 3.8.



Figure 3.8. A variety of flat-plate solar distillation units (solar stills) at the study site in the Namib Desert.

The period from 1960 to the 80s saw a lot of developments in this technique particularly targeted towards enhancing the performance of the distillation units. All the resulting variations of the solar still can be grouped into three general categories namely;

- *stills with concentrating collectors, and with insulated glazing*: where a parabolic mirror is used to reflect sunlight onto an enclosed evaporation vessel or in the latter where an insulated cover is put over the glazing at night- allowing distillation to continue into the evenings and also for distillation to start earlier the next day because of a better heat retention;
- *multiple tray tilted stills*: a series of shallow horizontal black trays in which the vapour from all the trays collects on the single transparent glazing and is then channelled to the storage unit;
- *tilted wick solar still*: solar distillation units lined with thin fibres that enhance the distribution of the feed water over the sun-exposed cover through capillary action.

Some other techniques include for instance *membrane distillation*, where a hydrophobic microporous membrane separates heated and cold streams of water (Belfort and Heath, 1993; Mulder, 1993 and Kunikane et al., 1994), Figure 3.9.

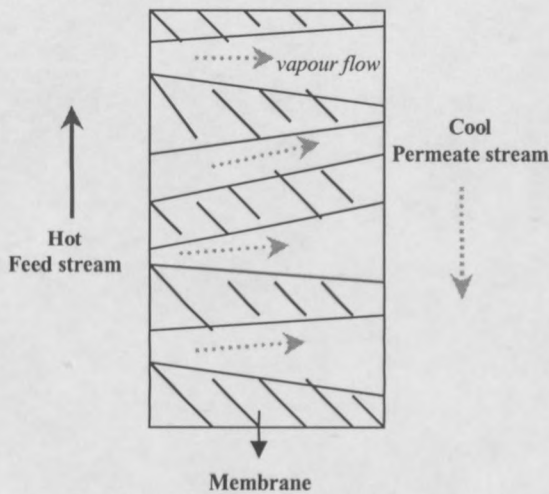


Figure 3.9. A Schematic presentation of the concept of membrane distillation

The membrane prevents the liquid from going through the pores whilst allowing water vapour to go through and condense on the colder side where it eventually drains as the product water. The earlier work by Japanese researchers was on cooling water by permeation through non-porous membranes into a partial vacuum during pervaporation (Hogan et al., 1992).

Most of the work on the variations in the solar distillation devices is reviewed by Malik (1982), McCracken (1985), El-Kassaby (1991), Tiwari (1992) and in Chaibi (2000). These reviews all re-affirm that the basic solar still design has the optimal cost of water production and that often alterations to this basic design make the system a lot too complex to maintain, without having any substantial effect on the production and are therefore not cost-effective. As a result, most of the current research has concentrated mainly on replacement of materials used in the main cost components of the solar stills with cheaper or readily available alternative material in order to reduce the price of the solar stills and henceforth the cost of water production.

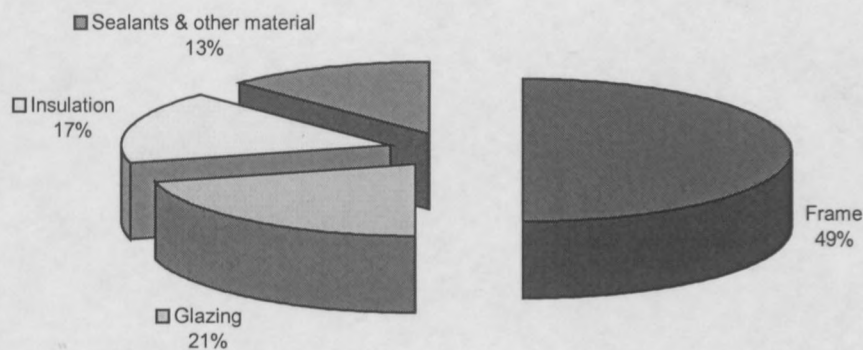


Figure 3.10. Approximate cost distribution of a typical solar still {based on this study and McCracken & Gordes (1985)}.

This study looked at some cheaper alternative framing material, which is the main cost component in the manufacture of solar stills, as well as alternative polymeric insulation materials that could be used by poor rural communities in Namibia.

3.3 Conclusions and Recommendations

The investigation of alternative sources of freshwater in arid regions has seen many ingenious innovations that can improve access to potable water in these regions. Some of these are directly applicable to remote rural settlements in these areas; however, a lot of them need to be re-adjusted to fit the mostly poor and unskilled people of these areas. These solutions would also benefit from a more holistic approach that would make use of current developments in the water treatment industry as well as the management field such as water conservation and demand management strategies.

PV-operated RO, simple solar stills and collection of fog water are some of the technologies that can be used in areas such as the Namib Desert. This study look at these options in order to contribute to knowledge on the potential of conjunctive use of these water sources, that is, non-conventional sources such as small-scale saline groundwater desalination and fog collection being used to supplement the conventional groundwater sources. This kind of approach would contribute to a better *diversification of alternatives* that is necessary for water self-security in these areas.

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CHAPTERS 4 - 6: PUBLICATIONS

These chapters present the publications that have emanated from this study and are either published in the listed conference proceedings or submitted to the listed Journals. The publications are presented in the following order; Chapter 4 is the problem definition while Chapters 5 and 6 present results of investigations of the feasibility studies of some possible solutions namely, solar desalination and fog collection, respectively. Each publication explains the motivation for the investigation as well as provides the detailed research methodology. A summary of the main research findings and conclusions is presented in chapter 7.

CHAPTERS 4: PROBLEM DEFINITION (HYDROCHEMISTRY)



4.1 Major-ion chemistry and groundwater salinization in ephemeral floodplains in some arid regions of Namibia; Shanyengana, E.S., Seely, M.K., Sanderson, R.D.

.....*Journal of Arid environments* (ACADEMIC PRESS).....Submitted

4.1 Major-ion chemistry and groundwater salinization in ephemeral floodplains in some arid regions of Namibia; Shanyengana, E.S., Seely, M.K., Sanderson, R.D.

.....*Journal of Arid environments* (ACADEMIC PRESS)

¹*Desert Research Foundation of Namibia (DRFN), P.O. Box 20232, Windhoek, Namibia*

²*UNESCO-associated Centre for Macromolecules and Materials, University of Stellenbosch, South Africa*

Abstract:

Groundwater quality in drinking water sources within ephemeral flood plains in the Namib and north central Namibia displays seasonal and spatial variation. Monthly Total Dissolved Solids (TDS) variation in individual sources ranges between 5 and 65% in north central Namibia and between 0.5 and 85% in the Namib sources. A higher monthly TDS variation, close to 500% increase, is recorded in slightly deeper as well as over-pumped freshwater sources in both study sites. The lowest TDS values are recorded during the rain season, i.e., after the rains for north central Namibia and only after flood events for sources in the lower rainfall Namib. Groundwater salinization in both sites is generally characterised by a shift from 'fresh' to 'very saline' groundwater, and a chemical evolution from Na and Ca-HCO₃ waters towards Na-Cl ones. The dominant processes that determine these hydrochemical shifts are refreshing by recharge waters, concentration by evaporation, dissolution of saline sediments (mainly evaporites), and mixing with older and more saline groundwater.

Keywords: *Namibia; arid regions; ephemeral floodplain; hydrochemistry; salinization*

¹ e-mail: cshanyengana@hotmail.com; Fax: +264 (061) 230172

4.1.1 Introduction

Fresh groundwater in most of Namibia is minimal and is found mainly along ephemeral river flood plains (DWA, 1995). Many rural and urban centres rely on these ephemeral river-based groundwater sources for their water supply (Jacobson et al., 1995). However, these water sources are subject to seasonal salinization and as a result, are often too saline for general domestic purposes (Shanyengana, 1997).

A few publications report on the hydrochemistry in both study areas. GCS (1991 & 1992) discuss general groundwater investigations in north central Namibia while others such as Hugo (1968 & 1970) report on brine explorations in this area. Day (1993) and Grobelaar & Seely (1980) present the major-ion chemistry of some water systems in the Namib Desert. Groundwater salinization in both areas, particularly its seasonal trends and processes of salinization, are however poorly understood.

This study investigates the hydrochemistry in drinking water sources of parts of north central Namibia and the Namib Desert where groundwater is accessed mainly through hand-dug wells and boreholes that are sunk along the ephemeral river basins. The paper discusses the processes and mechanisms of groundwater salinization as well as chemical evolution of the groundwater in these sources.

4.1.2 Material and Methods

Study area

Water resources in Namibia

Ninety seven Percent of Namibia is arid to semi-arid (Hutchinson, 1995 and Heyns et al., 1998). Rainfall is low and highly variable and, as a consequence, no perennial rivers originate from within the country's borders, Figure. 2.2

Most urban and rural centres rely on ephemeral rivers for water supply. The water is accessed either through surface dams or boreholes that are sunk within the river basins.

Fig. 4.1.1 is a simplified cross section of typical alluvial aquifers that are found in these ephemeral rivers.

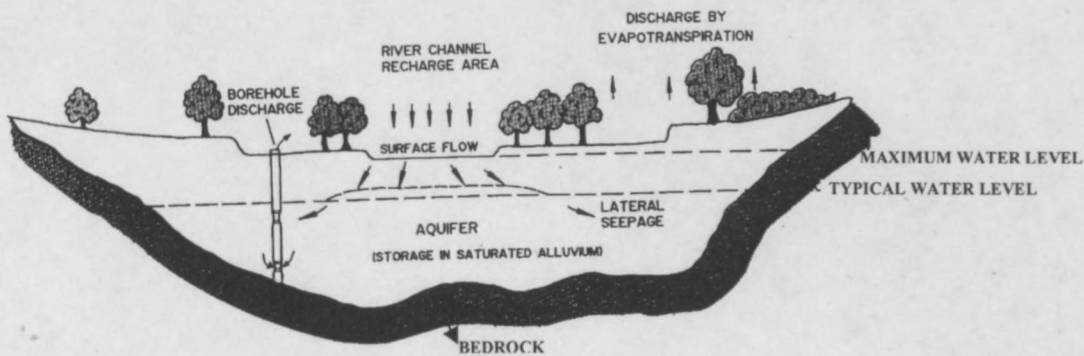


Figure 4.1.1. A generalised sketch of alluvial aquifers found in ephemeral rivers of Namibia (Source: Jacobson et al., 1995).

North central Namibia

North central Namibia is semi-arid. Rainfall averages about 400 mm per year at the study site, however, it is irregular and exhibits high temporal variability (ZSW, 1998). Records at the nearest long-term weather station at Ondangua indicate an absolute maximum and minimum of 982 and 184 mm per year, respectively. The area has an average potential evaporation of 2600 mm per year and its annual water balance shows a water deficit in eleven out of twelve months (DWA, 1990 and Hutchinson, 1995).

This site comprises of ephemeral rivers and pans that are locally known as *oshana* and *Eendobe*, respectively. Oshanas are a series of ephemeral inland drainage channels whilst pans are shallow depressions that are found within the oshana flood plain. The flood plain is linked to an inland salt lake, Etosha, at its terminus. The Groundwater in the area is generally saline owing to dissolution of evaporites (evaporitic precipitates) and saline lacustrine sediments that are found on the oshana and pan floors (GCS, 1992).

The artesian sources are linked to saline artesian groundwater sources (DWA, 1995). Water samples were collected from the artesian sources at Oshivelo and from hand-dug wells in the neighbouring villages.

Central Namib desert

The central Namib is an arid region. Rainfall is low and highly variable and averages about 27 mm at Gobabeb (Lancaster et al., 1984). The area has an average potential evaporation of about 3 000 mm per year and its annual water balance shows a water deficit throughout the year (Lancaster et al., 1984).

Groundwater is generally saline and, as a result, freshwater availability restricts both small and large-scale development activities in the area. Water samples were obtained from boreholes along the Kuiseb river, at settlements of the local inhabitants and at the Gobabeb Training & Research Centre (GTRC).

Sample collection and analysis

A total of eighty water samples were obtained from shallow boreholes and wells (water level 10 - 23 meters) in north central Namibia and the central Namib Desert on a monthly basis, from September 1998 to September 2000. All samples were analysed for major ions, TDS and electrical conductivity (EC). Major ions were determined by atomic absorption spectroscopy, using direct flame and with a Skalar San Plus automatic analyser. TDS was determined by evaporating the sample and drying it at 180° C while EC was measured with a Crison Micro CN 2200 electrode.

4.1.3 Results

4.1.3.1 TDS and major ions

Groundwater in water sources (depth 10 -19 meters) of the Namib and north central Namibia displays seasonal variation in total dissolved solids (TDS) (Fig. 4.1.2). The variation is characterised by low TDS groundwater at the beginning of the rain season and a higher and increasing TDS most of the year until the next rain season. TDS values in sources of north central Namibia range from 148 to 10 300 mg/l and 239 to 10 888 mg/l in the Namib. Monthly TDS variation in individual sources is between 5% and 65% in north central Namibia and 0.5 and 85% in the Namib sources.

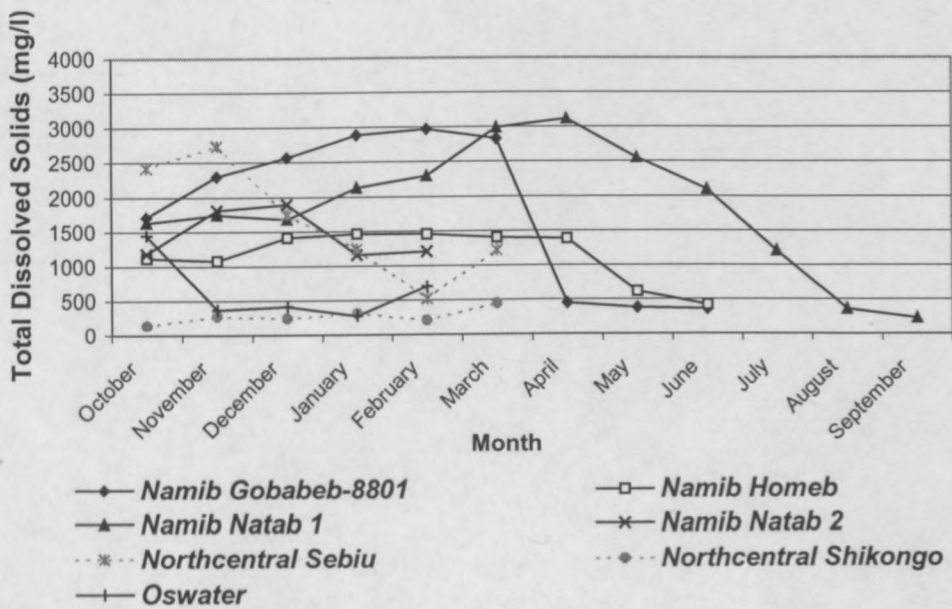


Figure 4.1.2. Total Dissolved Solids (TDS) in groundwater sources of the Namib Desert and north central Namibia.

Both study sites also have water sources that display much higher TDS and TDS variation, particularly during the later part of the dry season, Fig. 4.1.3.

This situation is observed in slightly deeper water sources (water level = 20 - 23 metres) in north central Namibia, and in over-pumped ones in the Namib. Maximum TDS and monthly TDS variation in these sources is about 11 000 mg/l and 500%, respectively.

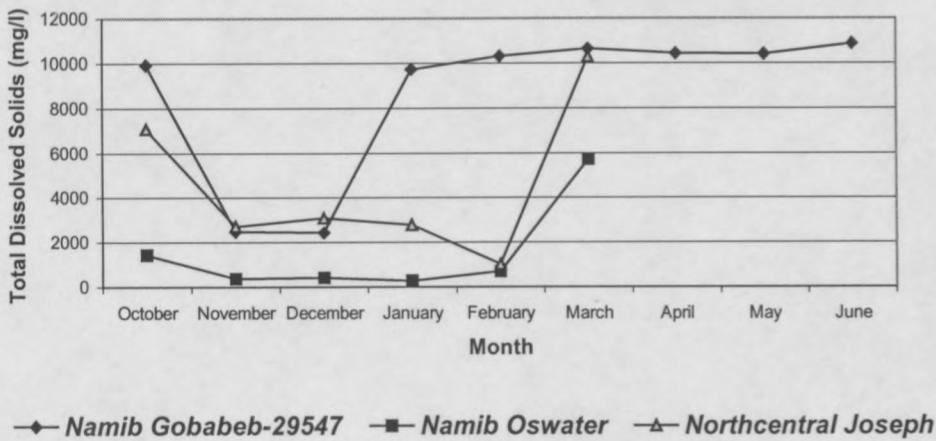


Figure 4.1.3 Total Dissolved Solids (TDS) in over-pumped and slightly deeper groundwater sources of the Namib Desert and north central Namibia.

4.1.3.2. Chemical evolution

Piper diagrams can be used to determine similarities in chemical properties and relations between different waters. In these diagrams, the total cations and anions of a given water are plotted as percentages in two base triangles which are then projected onto a single grid in order to identify if there are similarities in their chemical compositions e.g. water types. The diagrams are also used to indicate chemical changes in the water, particularly ion exchange and salinisation that could be due to mixing or intrusion by deeper, more saline waters.

The waters from the study sites are presented in Piper diagrams below. Fig. 4.1.4 (a) - (c). Figure 4.1.4 (a) presents data from fresh and saline water sources in north central Namibia and b) from the Namib desert.

Figure 4.1.4 (c) displays the distribution of fresh and saline water end-members (the observed hydrochemical extremes) in both study areas. Rainfall data from the Namib was not available at time of publishing.

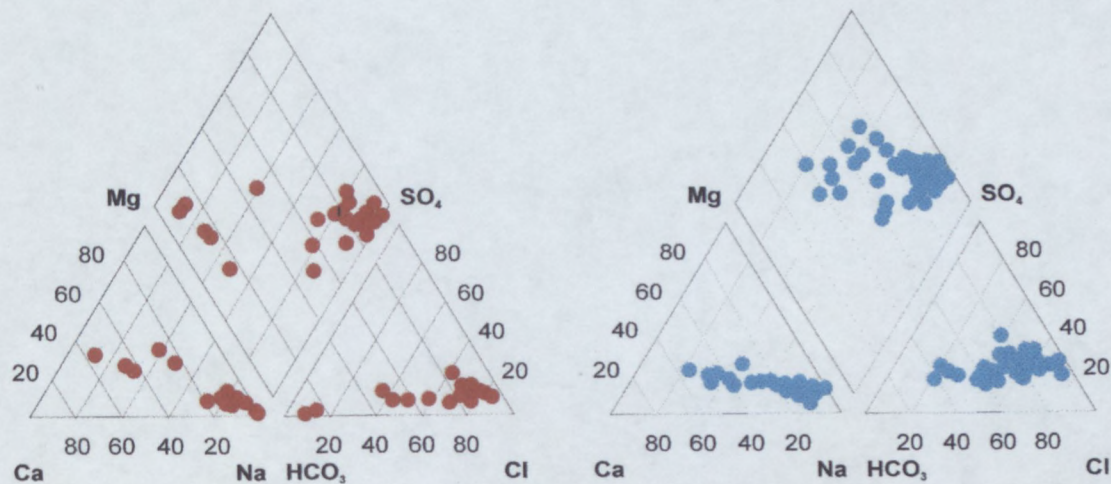


Figure 4.1.4(a) Piper plot of water from north central Namibia 4.1.4 (b) Namib Desert

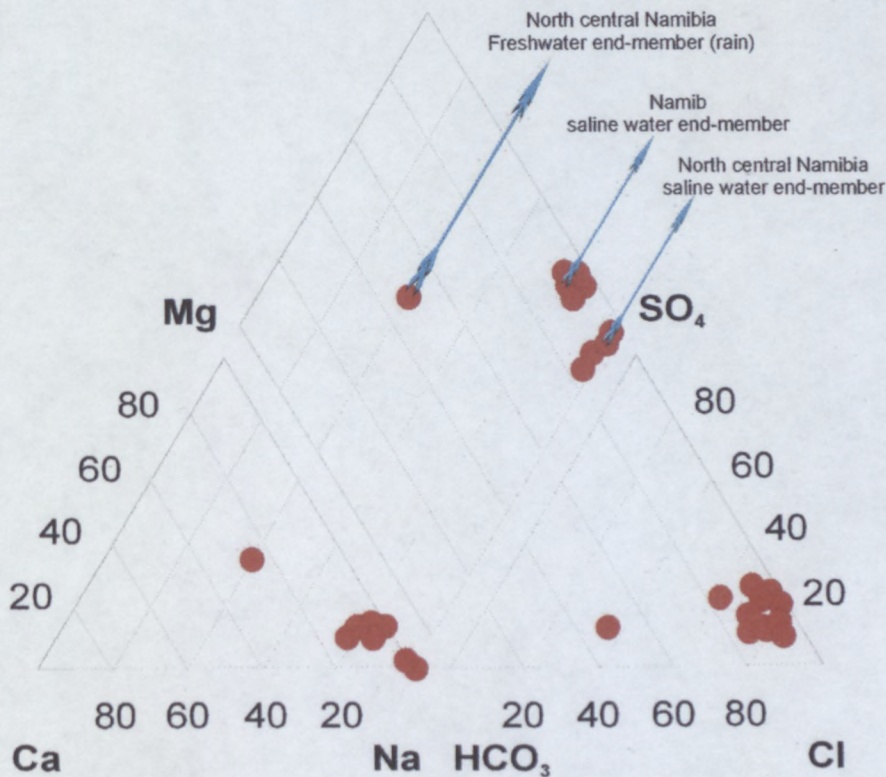


Figure 4.1.4 (c) freshwater and saline water end-members of each site

4.1.4 Discussion

4.1.4.1 Salinization

Water salinization refers to an increase in TDS and overall chemical content of water (Richter and Kreitler, 1993). Groundwater salinity in this paper is presented according to the classification of Robinove et al., 1958, Table 4.1.1

Table 4.1.1. Water quality classification based on Robinove et al. (1958)

Class	TDS range (mg/l)
<i>Fresh</i>	0 - 1 000
<i>Slightly saline</i>	1 000 - 3 000
<i>Moderately saline</i>	3 000 - 10 000
<i>Very saline</i>	10 000 - 35 000
<i>Briny</i>	> 35 000

The groundwater quality in most shallow water sources changes from fresh to slightly saline and finally to moderately saline in response to recharge by rainfall and floods, and then salinization during the latter part of the year.

Water in slightly deeper and over-pumped sources varies between moderately saline to very saline (Fig. 4.1.3). The deeper sources are possibly drilled past the freshwater section into the saline water ones, permitting upward migration of saline groundwater. The high groundwater TDS in over-pumped sources can be attributed to pumping-induced intrusion by deeper, more saline waters. Both these cases are reported in other arid areas (e.g. Kelly, 1974; Newport, 1977; Atkinson et al., 1986; Waddel & Maxwell, 1988 and Richter and Kreitler, 1993). Indeed, they agree with earlier findings that arid regions often have saline groundwater underlying the fresh water resources (e.g. Wilmoth, 1972; Scalf et al., 1973; Newport, 1977 and Bednar, 1988).

4.1.4.2 Process of salinization

Changes in groundwater salinity and overall chemical composition occur along flow paths from recharge to discharge areas due to either natural and/or anthropogenic causes (Richter and Kreitler, 1993). Raindrops interact with atmospheric gases and particles whilst surface runoff interacts with mineral matter on its way to surface-water bodies, where it mixes with water of different chemical composition (Richter and Kreitler, 1993). Water that enters the soil is subject to chemical, physical and biological changes due to processes such as evapotranspiration, mineral solution, precipitation, solution of gases and mixing with resident waters.

Evaporation of surface water and moisture in the unsaturated zone has been found as the most influential process in the development of the chemical composition of shallow groundwater (Boyd & Kreitler, 1986 and Richter & Kreitler, 1993). Evaporation concentrates the remaining water and leads to precipitation and deposition of evaporites that are eventually leached into the saturated zone. This source of groundwater salinity is amplified in arid lands, such as the study sites, due to the high evaporation rate and low rainfall which encourage the above-mentioned processes and also lower or absence of flushing of saline water.

The processes and mechanisms that determine the composition of a water body can be identified from plots of ionic ratios, e.g., the $\text{Na}/(\text{Na} + \text{Ca})$ ratio Vs TDS plot proposed by Gibbs (1970).

A Gibbs plot of data from both study sites (Fig. 4.1.5) indicates that evaporation and precipitation are the dominant processes controlling the major-ion composition of groundwater in both sites. This is supported by earlier work, for instance, Grobelaar & Seely, (1980) and Day (1993) in the Namib, and Shaw (1988) and GCS (1992) in north central Namibia.

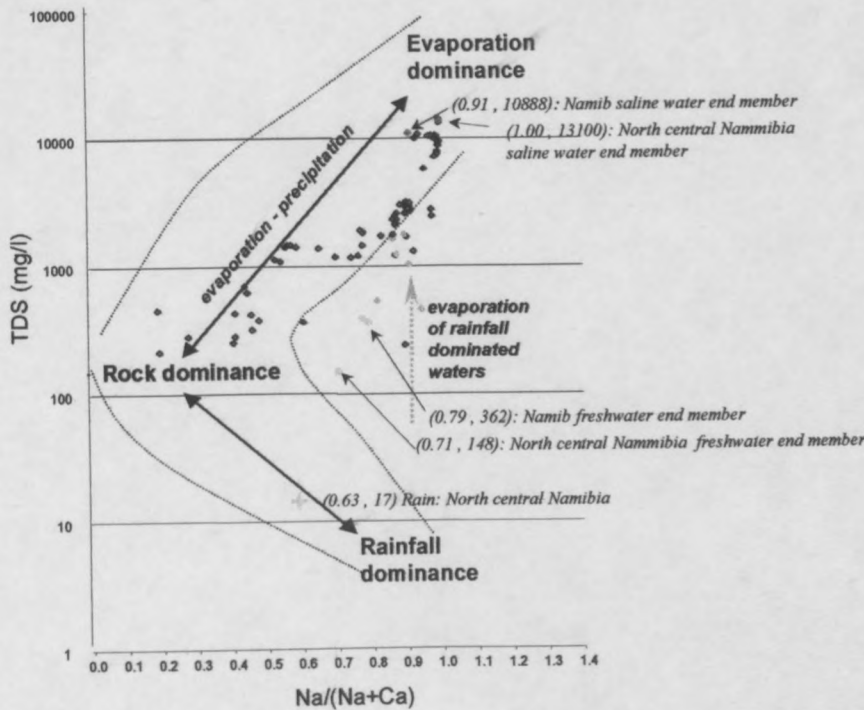


Figure 4.1.5. Gibbs (1970) plot indicating the mechanisms that determine the major-ion composition of groundwater in ephemeral river sources in north central Namibia and the Namib Desert.

The major-ion chemistry of fresh to slightly saline water sources in both study sites is controlled by evaporation of rainfall dominated waters while the Namib moderately saline to very saline groundwater shows evaporation and mineral precipitation as the dominant factors controlling composition. Waters from the artesian sources only plot in the evaporation dominance area and do not indicate any seasonal fluctuations. Indeed, this water is too deep to show any response to the local hydro-climatic conditions including local recharge.

The processes of groundwater salinization are often identified from ionic versus TDS plots such as Na/Cl Vs TDS or Cl (e.g. Jacks & Rajagopalan, 1996 and Shanyengana, 1997). Chloride is chemically conservative, that is, once in solution it is not easily removed by most processes other than precipitation at very late stages and, as a result, it is often used to monitor water quality changes and their sources (Hem, 1985; Morton, 1986 and Richter et al., 1990).

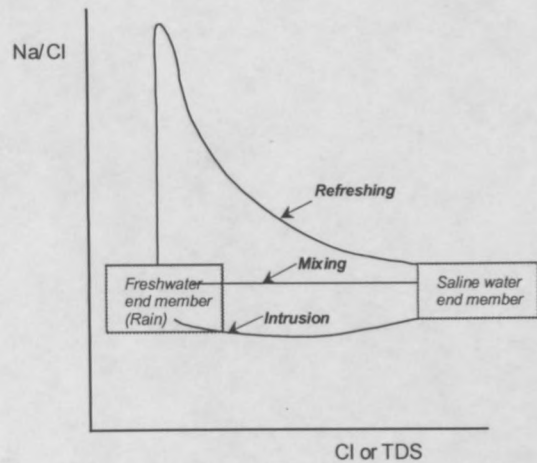


Figure 4.1.6 (a) Mechanisms of salinization that can be determined from Na/Cl ratio Vs Cl or TDS plots (after, Jacks & Rajagopalan, 1996).

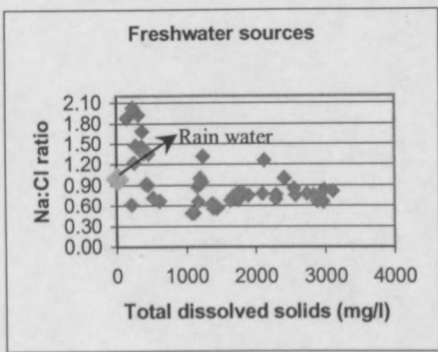


Figure 4.1.6 (b). North central Namibia water sources

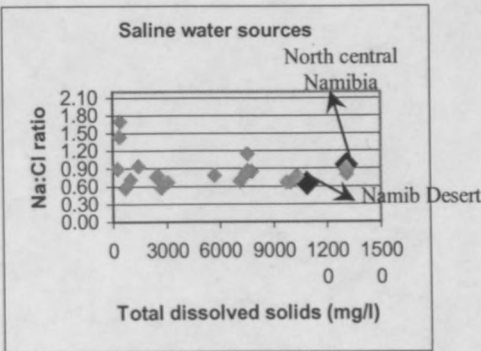


Figure 4.1.6 (c). Namib Desert water sources

Fresh to slightly saline groundwater sources in both study sites are refreshed by recharge water towards the freshwater end-members during the rain season either by direct rainfall or flooding. Thereafter, they are subject to mixing and at times intrusion by underlying saline water and, salinise towards the saline water end-members of each site, Fig. 4.1.7 (b).

The refreshing phase in freshwater sources of north central Namibia starts at the beginning of the rain season (September/October). In the Namib this phase only begins after flood events which normally occur between December and March.

The moderately saline to very saline sources show a short-lived refreshing phase that is followed by a mixing phase towards the saline water end-members. Most of these water sources, particularly the deeper sources, are very saline during most of the year except during parts of the rain season and during flood events when less saline recharge waters refresh them. However, even the recharge water is soon encroached by the surrounding saline water. This process is gradual, as well as season-dependent in well-utilised and non-pumped sources, and more rapid in cases where the water sources are pumped extensively (pumping-induced salinisation).

4.1.4.3 Major-ions and chemical evolution

Recharge groundwater in both study sites displays a lower major-ion concentration than that found in longer resident waters. Major-ion concentrations increase gradually from the end of the rain season towards the next, except in cases of intrusion where the increase is exponential.

This change is characterised by an increase, in order of increasing magnitude of concentrations of cations - anions, in Na, Mg, K - Cl, HCO_3 & SO_4 and Na, Ca, Mg, K - Cl, SO_4 & HCO_3 in freshwater sources of north central Namibia and the Namib, respectively.

Modified Piper diagrams (rotated axes) can be used to identify relations between groundwater sources as well as their chemical evolution and the processes responsible for the observed water quality changes (Richter and Kreitler, 1993). An altered Piper diagram of water sources in the study areas, Fig. 4.1.7, shows that fresh groundwater evolves towards the chemistry of the saline water end-members found in each area.

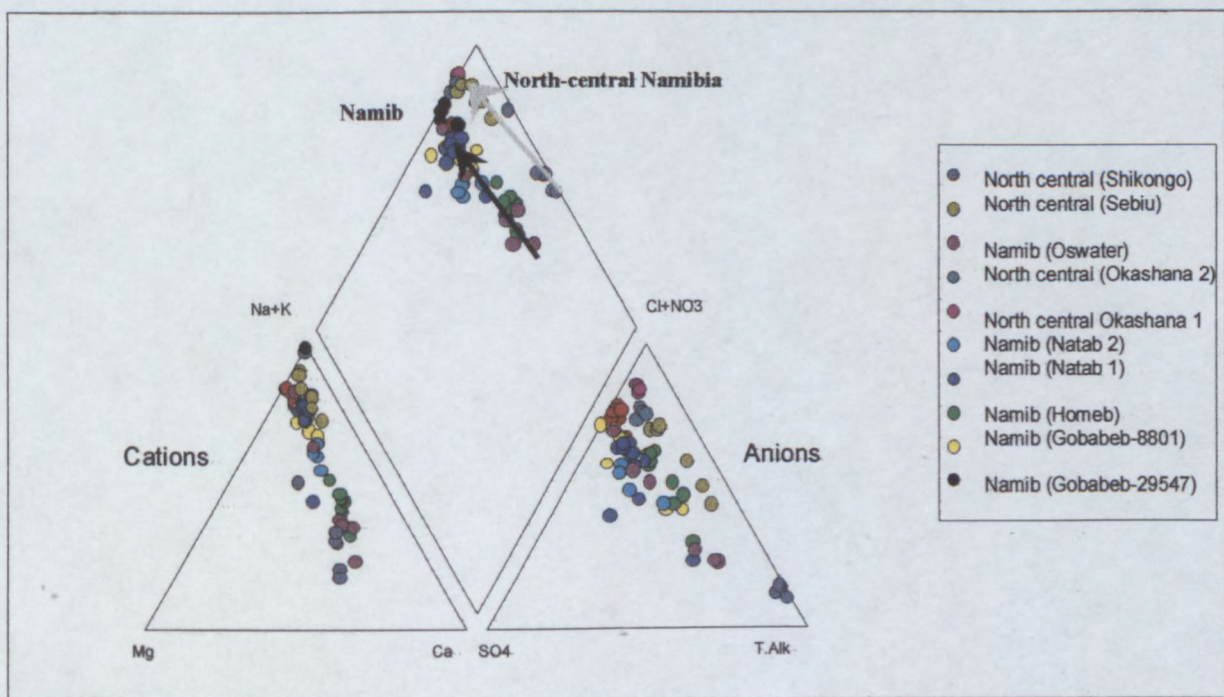


Figure 4.1.7 A modified piper plot indicating chemical evolution of fresh groundwater, in some of the water sources, towards the saline water end-members found in each study site.

Chemical evolution in freshwater sources of north central Namibia is generally from Na- HCO_3 -Cl to Na-Cl waters, while in the Namib it is from Na-Ca-Cl- HCO_3 and Na-Cl- SO_4 to a Na-Ca-Cl one.

This evolution is gradual in more shallow and well-utilised water sources, and rapid in water sources that are earlier reported as deeper or ones that record extensive pumping.

The dissolution of gases and minerals, particularly CO_2 and CO_3 -related compounds in the atmosphere and in the unsaturated zone during precipitation and infiltration, would impart the observed HCO_3 water type. Similarly, dissolution of evaporites and saline lacustrine sediments such as Halite (NaCl) and soda ash (Na_2CO_3) that are found on pan floors in north central Namibia, e.g. Hugo (1968) and GCS (1992) account for the dominant cation being Na in these sources. Dissolution of gypsum and halite in the Namib sources would account for Ca and Na being the dominant cations in this area e.g. Eckardt and Spiro (1998).

The loss of Ca- and HCO_3 - related minerals through precipitation of minerals such as CaCO_3 , and the conservative nature of chlorine favours formation of the Na-Cl water type that is observed in long resident waters of both study sites.

4.1.5 Summary

Shallow groundwater in Ephemeral river sources of arid lands display high seasonal and spatial TDS and major-ion variation. The variation is a function of direct recharge by rainfall in relatively high rainfall areas such as semi arid regions, and mainly surface runoff in the lower rainfall arid and hyper-arid areas. It appears that in low rainfall areas such as the Namib, the local rainfall does not effect any significant recharge and thus, no appreciable change in groundwater quality is recorded until after a flood event.

The groundwater quality is characterised by refreshing during the rain season and salinization during the remainder of the year. The water displays a chemical evolution from low TDS $\text{Ca}(\text{HCO}_3)_2$ recharge waters towards the chemistry of underlying saline water end-members which are typically of a Na-Cl or X-Cl water type (X being the dominant cation (s) in the local soil media).

Evaporation of recharge waters and dissolution of evaporites appear to be the dominant processes that determine the major ion composition in ephemeral river sources of arid lands. Consequently the local hydro-climatic conditions, namely rainfall and evaporation rate, are the primary determinants of groundwater quality and can thus be used to estimate groundwater salinity in shallow water sources of these regions. However, these estimates would be lower than the actual values in case of deeper and over-pumped water sources due to intrusion by older, more saline waters, and in areas that have experienced other significant geochemistry-altering activity e.g. volcanism.

4.1.6 Acknowledgements

We are grateful to Namwater, particularly to Mrs. Merylinda Conradie for the water chemistry analysis. The following water chemists are also thanked for reviewing the manuscript namely, Dr. Gideon Tredoux of the Council for Science and Industrial Research (CSIR), South Africa and Prof. Dr. Gunnar Jacks of the Royal Institute of Technology (KTH) Sweden. We are also thankful to Ms. Annabel Smith of the Royal Holloway University (Britain) and Mr. Mark Robertson of the DRFN, Namibia, for editing the manuscript.

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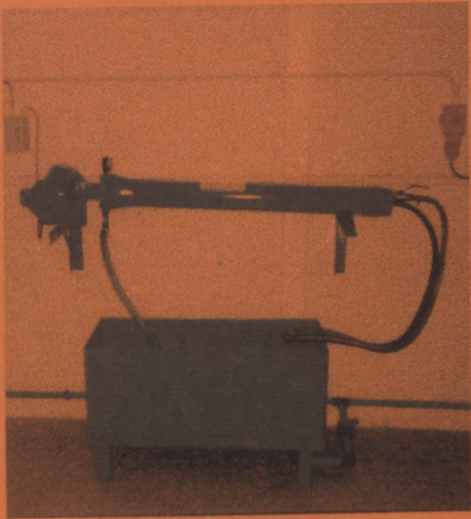
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CHAPTERS 5: SOLAR DESALINATION



5.1. Water supply options for rural settlements in the Namib Desert: *Solar-operated*

Desalination; Shanyengana, E.S., R.D. Sanderson and M.K. Seely.

.....*Desalination* (ELSEVIER) Submitted

5.1. Water supply options for rural settlements in the Namib Desert:

Solar-operated desalination

Shanyengana, E.S.^{a, b*}, R.D. Sanderson^b and M.K. Seely^a

^a*Desert Research Foundation of Namibia (DRFN), PO Box 20232, Windhoek, Namibia*

Website: <http://www.drfn.org>; Email: cshanyengana@hotmail.com

^b*UNESCO Associated Centre for Macromolecules & Materials, University of Stellenbosch, South Africa Website: <http://www.sun.ac.za>*

Abstract

Arid regions have limited surface and groundwater that is also often too saline water for human consumption. The shortage of potable water in these regions is more pronounced in remote rural settlements such as villages in the Namib Desert because the inhabitants cannot afford the conventional saline water treatment options. This paper presents findings of some small-scale desalination options that can be used in these areas. Investigations with alternative solar still materials and low pressure reverse osmosis show that it is possible to develop cheap and efficient desalination units that are affordable to these communities. The results also show that small-scale PV-operated reverse osmosis systems can be designed to operate at lower pressures, higher recoveries and permeate production than the current examples as reported in literature where small-scale RO is implemented.

Keywords: *Namibia; Desert environment; rural water supply; Small-scale solar desalination*

^{a*} corresponding author: cshanyengana@hotmail.com

5.1.1. Introduction

Inhabitants of arid regions face an ever-increasing shortage of good quality drinking water. The water situation is particularly bad in hyper arid environments such as the Namib Desert because the rainfall is minimal; surface water is ephemeral, occurring only for short periods during the year; and the groundwater is saline during most of the year. This scarcity of freshwater is even more pronounced in remote villages (rural settlements) because most of the current solutions are still too expensive for these areas and would require skilled labour and expertise (GWP, 2000).

This paper discusses investigations of small-scale desalination options for remote rural areas in the Namib Desert, which include low operating pressure reverse osmosis and desalination with inexpensive solar distillation units. The paper aims to contribute to current international research efforts to make safe drinking water affordable to remote settlements in arid areas.

5.1.2. Background

Three percent of world water resources are freshwater, however, most of this water is not accessible because it is bound in icecaps and glaciers, and only a much smaller percentage of this total, about 19%, is available as surface and subsurface water (Agnew & Anderson, 1992 and Gleick, 1999). The water situation is even worse in arid lands because most of the available water is saline and would require energy intensive treatment such as desalination to make it fit for domestic use (Uitto and Schneider, 1997).

Current research concentrates on the use of renewable energies such as solar, wind and ocean wave energy, and more recently, co-generation and the use of nuclear energy to power desalination processes (Childs & Dabiri, 1998; Voivantas et al., 1999; Med. conf., 2000 and Semiat, 2000). Solar energy is a more appropriate energy source for the remote villages in the Namib Desert where sunshine is abundant. Solar desalination for remote areas is currently receiving world attention and most of the success is reported in places such as Australia, Botswana, The Canary Islands and Greece (Yates et al., 1998; Chaibi, 2000; Herold et al., 2000 and Goen Ho, 2001). It has also been the subject of several international conferences (Med. conf., 2000).

5.1.3. Material and methods

The study used solar distillation basins and a small reverse osmosis unit to investigate the feasibility of inexpensive solar-operated desalination for water supply to villages in remote areas of the Namib Desert.

5.1.3.1 Reverse osmosis

Small-scale desalination laboratory trials were conducted with a reverse osmosis unit having a polyamide spiral-wound membrane that was developed by GrahamTek Mineral Water Development (MWD) in Stellenbosch, South Africa, Figure 2.4.

Experiments were carried out in the laboratory for a few hours to investigate the feasibility of desalinating saline groundwater at an operating pressure that can be delivered by a photovoltaic-operated pump.

An operating pressure of 6 bar was chosen because the most appropriate pumps have a maximum operating pressure of between 6.2 - 6.9 bar [3]. Sea salt was added to the feed water, steadily increasing the total dissolved solids (TDS) from about 4000 mg/l to 13000 mg/l. The following parameters were then recorded; TDS of feed water and product water, and the flow rate of the product water (yield) and the reject water.

5.1.3.2 Solar distillation

Solar stills were constructed according to the specifications of McCracken and Gordes (1985) with deviations from some of the proposed materials such as the galvanised steel bottom covering and aluminium frames. The stills had surface areas of about 1.6 m² and were made with PVC & u-PVC window framing and fibreglass. The insulation was made from polyurethane, polystyrene and cotton wool, Figure 5.1.1.

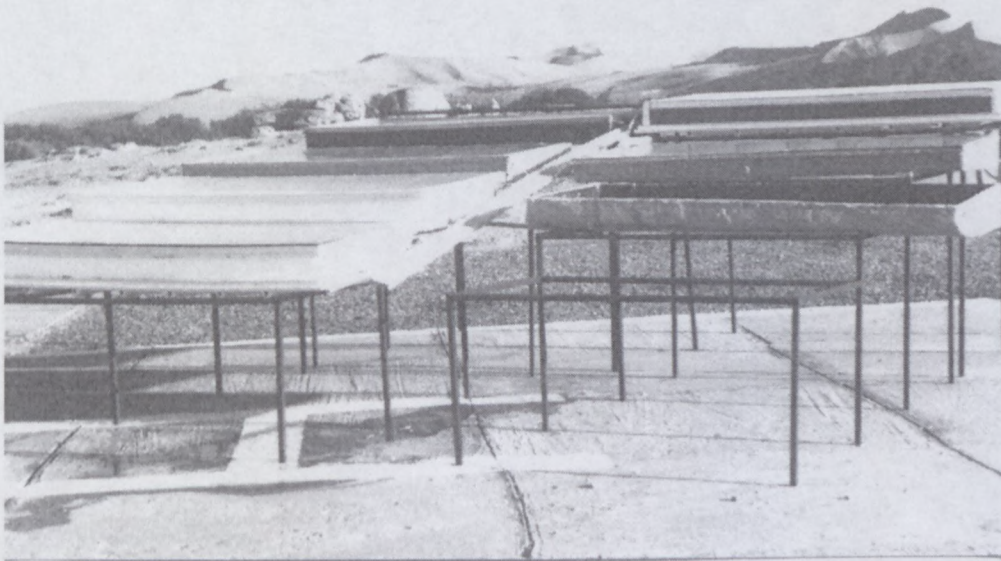


Figure 5.1.1. Solar stills constructed with different framing and insulation material

The performance and durability of the various stills were monitored, and the best one was operated alongside a McCracken solar still for one month in order to determine how it compares to the latter. The potential annual yield of this unit was then calculated from correlation of measurements of yield and solar radiation.

5.1.4. Results and Discussion

5.1.4.1 Reverse osmosis

The results of low-pressure desalination with the RO unit are presented in Fig. 5.1.2.

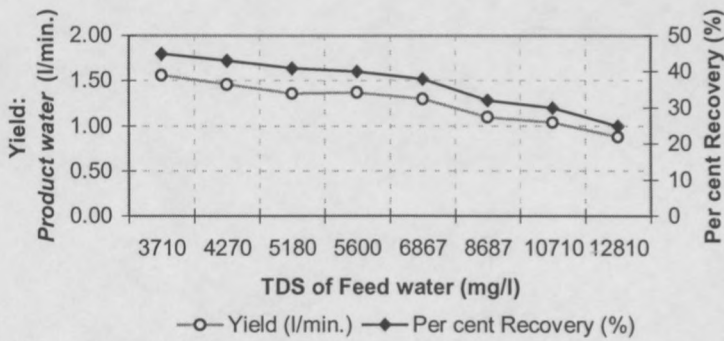


Figure 5.1.2. Reverse osmosis desalination at an operating pressure of 6 bar and varying TDS of feed water.

The yield and percent recovery decreases with increasing feed water salinity. The unit records an average yield of 1.3 litres per minute (a range of 0.9 to 1.6 l/min.) of 85 mg/l (30 - 210 mg/l) TDS product water and a recovery of 37% (25% - 45%) from feed water of a TDS of 7230 mg/l (4000 - 13000 mg/l).

The results indicate that it is possible to desalinate saline water at a low operating pressure while still maintaining a satisfactory yield. Given the annual average of about 10 hours of sunshine per day in the Namib Desert (Lancaster et al. 1984), these results translate to a possible daily average production of the PV-operated unit of about 4600 litres per day (1286 - 16000) of 500 mg/l TDS product water.

The actual PV-operated unit could produce only between 60% and 80% of the total volume obtained during the controlled laboratory tests (i.e., about 2500 - 3500 l/day) considering that peak performance could be unattainable in field conditions due to variation in the relevant climatic factors and also the long-term performance of the membrane. This yield is, however, still within the average daily water demand of villages in the Namib Desert which is about 22 - 30 litres per person per day and 700 to 2300 litres per village per day (Henschel et al., 1998).

The unit operates at the lower end of the operating pressure of typical small-scale Brackish Water Reverse Osmosis (BWRO) systems and produces more water and would also have a lower cost of water production than similar units that are reported in literature (e.g. Med. conf., 2000; Goen Ho, 2001 and Mathew et al., 2001). However, this efficiency and overall energy consumption of the PV-operated RO system can still be improved by incorporating energy recovery equipment (Childs & Dabiri, 1998 and Glueckstern, 1999). This would account for a significant contribution because with the given recovery rate, more than 50% of the energy is lost in the brine stream.

5.1.4.2 Solar distillation

The different solar stills all show an equal yield, however, only the stills made with u-PVC frame and polyurethane insulation (the new still) last longer and are therefore, suitable for use in solar distillation units. A PVC frame tends to become more flexible and lose its rigid form with exposure to the sun while the fibreglass unit develops cracks, particularly when it is used for the bottom covering.

Equally, Polystyrene foam does not withstand the high temperatures inside the still and begins to disintegrate within a few days particularly along and underneath the silicone sealant where more heat is likely to accumulate, Figure 5.1.3.

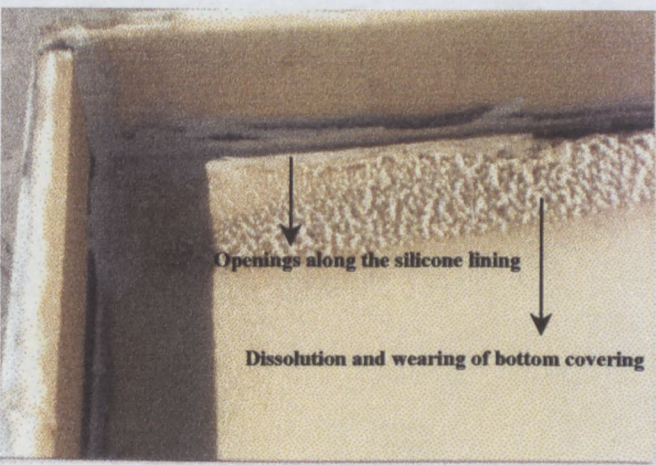


Figure 5.1.3. An example of some of the problems encountered with polystyrene insulation

Figure 5.1.4. shows that water production in the new still is about 88% ±12 that of the McCracken still.

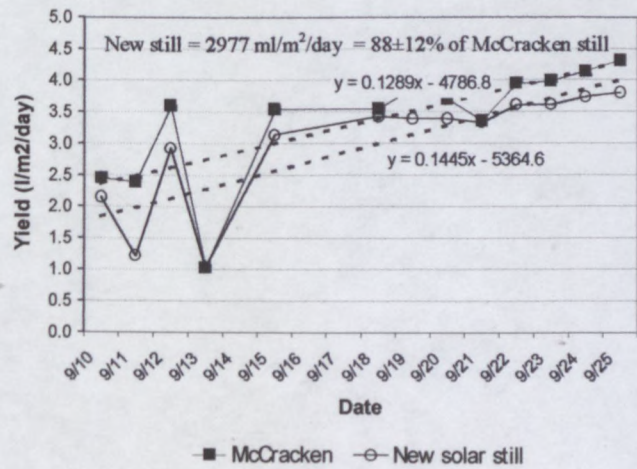


Figure 5.1.4. Solar distillation in a McCracken solar still and the new, cheaper still of equal surface area.

The small difference in the two stills can be ignored because the new still is about four times cheaper than the McCracken one and thus it has a much lower unit cost of water production.

It is also worth noting that these experiments were conducted during winter when solar radiation is at its lowest and as a result, they do not reflect conditions during most of the year. The expected daily water production of the solar still throughout the year at some locations in Namibia is presented in Figure 5.1.5. These estimates are based on derivations from similar solar distillation experiments in Madani (Greece), Stellenbosch (South Africa) and Howe-Texas County (USA); and long-term solar radiation readings at Gobabeb, Keetmanshoop, Walvis Bay and Windhoek (Namibia) from Lancaster et al. (1984), Goldie (2001) and Redmund et al. (2001).

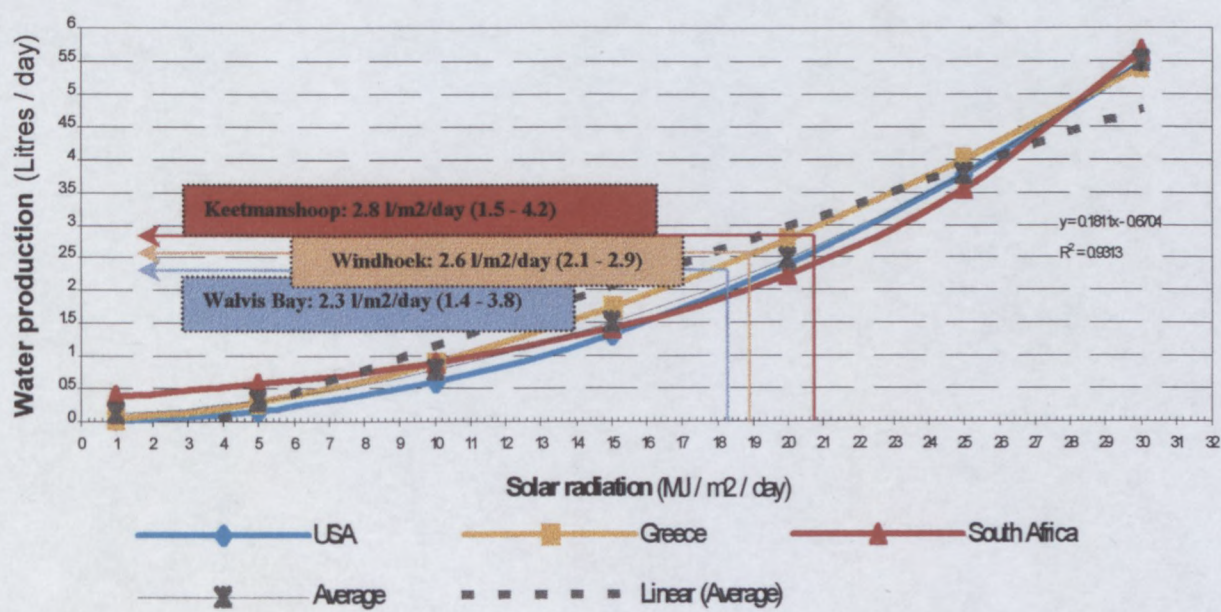


Figure 5.1.5. Solar still water production in Madani (Greece), Stellenbosch (South Africa) and Howe- Texas County (USA); and estimated production at sites in Namibia.

The graph shows that the new solar still would have an average daily water production of about 2 l/m²/day at Walvis Bay, the closest point to the study site where long-term solar radiation was available.

The highest average yield is expected in Keetmanshoop and the lowest yield in Walvis Bay because even though this area is within the hyper arid part of the country, the solar radiation is reduced due to the higher relative humidity and foggy conditions that often prevail.

Indeed, the yield is expected to be slightly higher at Gobabeb because it is about 60 km inland and thus, not as much affected by the coastal weather.

5.1.5 Summary

Both the solar still and PV-operated RO unit would appear expensive for rural areas if one only considers the initial capital investment, i.e. 75 US\$ (ca. 25 US\$/litre/day = 200 South African Rand /litre/day) and 2500 US\$ (ca. 0.83 US\$/litre/day = 6.6 SAR), respectively. Such an analyses is, however, misleading because it does not consider that solar stills could have an operational life span of 5 to 10 years or more, and between 3 and 5 years for the RO membrane, depending on the maintenance. For comparison sake, operations over five years would represent a unit cost of water of about 110 SAR/m³ (ca. 0.11 SAR/litre) for the solar still and about 3.6 SAR/m³ (ca. 0.004 SAR/litre) for the PV-operated unit. This is rather expensive even compared to the current water pricing for instance in Walvis Bay which is about SAR 2.5 / m³ (Steenkamp, 2001). The prices are however, still reasonable because these areas do not have access to the town supply and the local groundwater is also too saline for human use. In addition, the total benefits of such systems also have to be considered such as the reduced occurrence of poor water quality related health problems, and that less time is spent travelling the usual long distances to fetch potable water. Instead there is more time allocated to family and community services.

5.1.6. Conclusions

Small-scale desalination units can be used to provide water and improve the socio-economic conditions of remote rural communities in arid regions.

The use of cheaper material such as u-PVC frames does not have a significant effect on the efficiency of the solar distillation unit and can therefore be used to reduce the cost of solar stills to make them affordable for poor rural households.

Similarly a PV-operated MWD unit is feasible and estimates indicate that such a unit would perform well above the average performance of current PV-operated units. Small adjustments such as energy recovery from the brine stream (e.g. Childs & Dabiri, 1988 and Glueckstern, 1999), can also be incorporated in order to reduce the overall energy consumption and allow for a better performance even during periods of cloud cover or for short periods after sunset. The PV-RO unit would, however, require a higher initial capital investment than the solar stills and is therefore only appropriate and cost effective for groups of households, schools or other rural groupings, in which case the initial capital investment is shared among many households and therefore the unit cost of water production becomes much lower than that of a solar still.

5.1.7. Acknowledgements

The authors would like to thank *GrahamTek*- Mineral Water Development, Stellenbosch, for making their RO unit available for the experiments and for the assistance they rendered during the investigations. We are equally grateful to Namib Windows, Swakopmund, for providing the u-PVC frames that were used to construct some of the solar stills.

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CHAPTERS 6: FOG COLLECTION



*Lessons from
nature*

Implementation

*Improved
understanding*

6.1. Shanyengana, E.S., Henschel, J. R., Mtuleni, V. S., Mwenya, E. & Seely, M.K. 2001.

Exploring fog as a supplementary water source in Namibia (*A Summary of fog collection in Namibia & the Namfog programme*).....*Proceedings of 2nd International conference on fog and fog collection*, July 20001. St. John's, Canada.

6.2. Shanyengana, E.S. Henschel, J. R. Seely, M.K. and Sanderson, R.D. **Exploring fog as a supplementary water source in Namibia (*Fog & groundwater chemistry: mixing for water supply*).....***Journal of Atmospheric Research*

6.3. Shanyengana, E.S., R.D. Sanderson and M.K. Seely. **Atmospheric moisture collection for water supply: *prototype collectors*...***Water International (IWRA)*

6.4. Shanyengana, E.S., Sanderson, R.D., Seely, M.K. and R.S. Schemenauer. **Testing greenhouse shade nets in collection of fog water for water supply.....***Journal of Water Supply: Research & Technology- AQUA (IWA Publishing)*

6.1. Exploring fog as a supplementary water source in Namibia: (*A Summary of fog collection in Namibia & the Namfog programme*); Shanyengana, E.S., Henschel, J.R., Mtuleni, V.S.,

Mwenya, E. & Seely, M.K.;

International Conference on Fog and Fog Collection,

St. John's, Canada. July 2001. Published

*Desert Research Foundation of Namibia,
Gobabeb Training and Research Centre,
P.O.Box 953, Walvis Bay, Namibia.
Email: drfn@drfn.org.na*

Abstract:

Namibia is an arid country, where fog has previously been identified as a feasible alternative source of water that could supplement existing traditional sources. The groundwater quantity and quality is impaired by the local hydro-climatic conditions: little and unpredictable rainfall and high evapo-transpiration. Coastal fog occurs in western Namibia during some 200 nights in a year and varies only by some 41% between years in comparison to a 133% coefficient of variation in rainfall. This makes fog a more reliable source of water than rainfall for many life forms. Potential sites for testing the application of fog water were identified, of which the primary test sites are located at villages of the indigenous Topnaar people and at the Gobabeb Training and Research Centre. Further tests were conducted along a 60 km transect extending from the coast. The gradually sloping and topographically featureless plain in the Namib fog zone differs substantially from its geographic counterpart in Chile and Peru, where the mountainous topography predictably enhances fog deposition at specific sites. In the Namib, fog deposition is not enhanced at a particular site and fog occurs anywhere across a large expanse of land. Another limiting factor in the Namib is the frequent occurrence of heavy windstorms.

Our current tests concentrate on improving fog collectors in terms of yield and durability, and on investigations of alternative fog collectors, better suited to Namib Desert conditions, while keeping costs low. We are also monitoring fog water quality over space and time in comparison to groundwater. Fog is a good source of supplementary water for rural and urban settlements in the Namib, but further knowledge of its peculiar properties in this area needs to be gained in order to facilitate its incorporation into the local water supply schemes.

6.1.1 Introduction

The Namibian coastal region is part of a desert environment, the Namib Desert, where sources of freshwater other than fog are scarce. Fog occurs along the coast and for some distance inland during most of the year. Its precipitation exceeds rainfall and as such, it presents a reliable supplementary source of water for communities in these areas. The ecological implications and uses of fog by fauna and flora in the Namib Desert have been investigated for a long time (Hamilton & Seely, 1976 and Seely et al., 1998). The investigations of fog collection for water supply to human settlements in the area, however, only began in 1995 (Henschel et al., 1998 and Seely & Henschel, 2000).

While it appears that the quantity and quality of fog water make this a potentially good source of potable water, suitable collectors with a durability of several years in the particularly aggressive weathering conditions of the Namib still need to be developed. These collectors can be adaptations of existing technology, or alternative fog collecting techniques. Concerted research efforts towards the conception and design of efficient collectors would stand to benefit many desert-dwelling people either through small-scale rural or bulk urban water supply schemes.

This paper presents an overview of the Namibian fog collection programme. It discusses general aspects of the programme and future plans which includes:

- investigation of fog collection potential at the coastal urban centres and inland, at rural settlements;
- adapting fog collectors to the special conditions of the Namib Desert, e.g., frequent windstorms;

- investigation of other types of collectors that would be suitable for the Namib conditions, e.g., prototype wind- and cooling-system based harvesters
- small- and large-scale applications.

6.1.2 Background

6.1.2.1 Climatology

Ninety seven percent of Namibia is arid to semi-arid. The central Namib is the most arid part of the country and rainfall is low and highly variable in time and space. Average annual rainfall is 18 mm at the coast at Swakopmund, and 21 mm 60 km inland at Gobabeb (Nagel, 1959 and Lancaster et al., 1984). However, rainless stretches of about ten years have also been recorded at Swakopmund (Nicholson, 1984). Rainfall decreases along an east–west gradient across the country, and is most variable at the west coast (Fig.6.1.1).

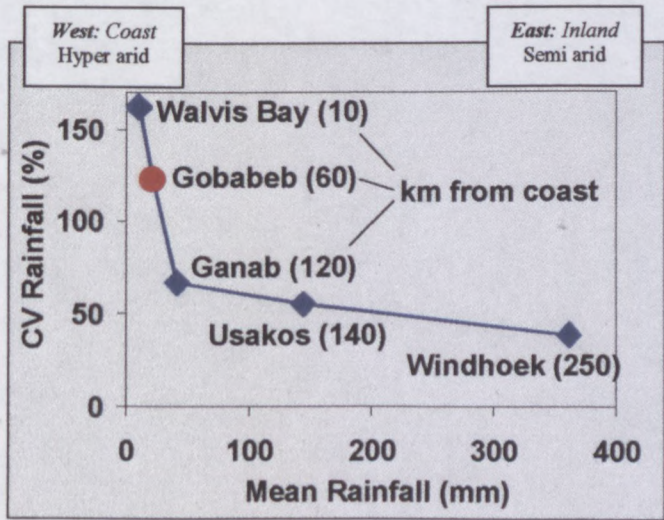


Figure 6.1.1: Coefficient of variation (CV) of rainfall from central Namibia (east) to the coast (west)

Fog occurs regularly in the Central Namib. Long-term records indicate that fog deposition exceeds annual rainfall about seven times at the coast, in Swakopmund, and almost two times 60 kilometres inland, at Gobabeb (Nagel, 1959 and Lancaster et al., 1984). It is more predictable than rainfall and indicates a coefficient of variation (CV) of only 41% between years, compared to a 133% CV for rainfall (Seely and Henschel, 2000).

6.1.2.2 The water situation

In the Namib, water of good drinking quality is scarce and is only found in ephemeral river aquifers. Groundwater is minimal, and often is too saline for human use. This water situation restrains both domestic and industrial activities in the area. Fog collection could contribute towards alleviating this water situation. The fog water can be used alone or mixed with the saline groundwater, to reduce its salinity. The latter is supported by studies that indicate that Namib fog water is of low chemical content, expressed as TDS (Seely et al., 1977 and Eckardt & Schemenauer, 1998). In inland areas, the fog season coincides with the period of high groundwater salinity (Figure 6.1.2), suiting for dilution of saline the groundwater with fog water.

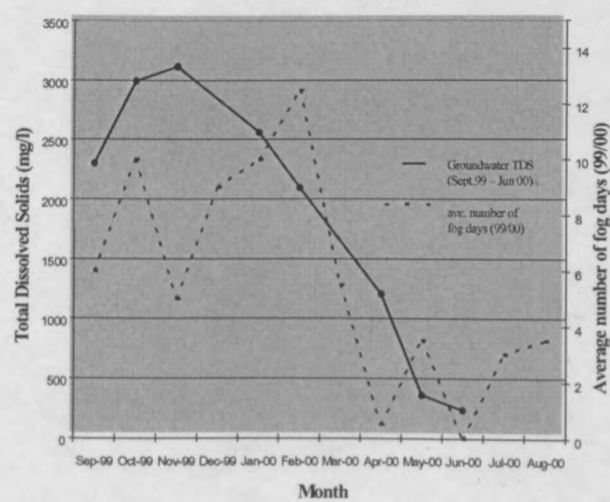


Figure 6.1.2: Groundwater salinity and frequency of fog occurrence at Gobabeb (Shanyengana ES, in preparation)

6.1.2.3 Constrains and limitations

Topography and nearness to the source of fog are some of the factors considered when selecting a site for a fog collection system. In Chile, such a system is within 5 – 25 km of the fog source, and at an altitude of between 400 to 1000 metres above sea level (m.a.s.l). where the highest liquid water content (LWC) and wind speed often occur (Schemenauer and Cereceda, 1982 & 1994). The mountainous topography predictably enhances fog deposition at certain sites. The situation in the Central Namib differs substantially from its geographic counterpart in Chile, because the gradually sloping and topographically featureless plains of the Namib make it difficult to predict fog deposition at any particular site in the fog zone.

These and other limitations such as the frequent occurrence of destructive sandstorms with peak wind speeds in the range of $24 - 32 \text{ m.s}^{-1}$, represent some of the constraining factors to successful implementation of fog collection systems in Namibia. Therefore, the programme is also investigating fog collection systems that would be better suited to conditions in the Namib.

6.1.3 Fog collection

6.1.3.1 Fog collection in endemic plants and animals

Fog is a key source of water for plants and animals in the Namib Desert (Louw, 1993; Seely & Henschel, 2000 and Henschel et al., in press). There are three main methods of harvesting atmospheric moisture, including fog, that are found in endemic fauna and flora of the Namib, namely;

- collecting fog on the body, e.g., fog-basking beetle *Onymacris unguicularis*, fog-absorbing leaves of the succulent shrub *Trianthema hereroensis*;
- enhancing fog water deposition on the substratum and drinking this, e.g., the beetle *Lepidochora kahani* which builds fog-water deposition ridges in sand, and dune grass *Stipagrostis sabulicola* dropping condensed fog water onto shallow roots;
- absorption of atmospheric moisture, e.g., beetle larvae and fishmoths.

Knowledge of some of the techniques and interactions of fog water and the natural collector surfaces would contribute to the understanding of fog droplet behaviour and surface interactions. This could be of major benefit for fog harvesting in general by contributing to development of more efficient harvesters.

6.1.3.2 Standard fog collectors (SFC)

Since October 1996, SFCs have been used to monitor fog deposition at long-term weather stations and some of the designated sites for fog water collection systems at Topnaar villages and the Gobabeb Training and Research Centre. Results indicate a strong seasonal variation in fog frequency and wetness, with most inland fog occurring from August to January, and the low period being February – July (Figure 6.1.3). The annual daily average at the designated sites is 0.5 – 3 litres/m²/day during fog events, and 0.1 – 1 litres/m²/day all year, i.e., including non-fog days (Henschel et al., 1998). No long-term SFC records exist for the coastal area, but measurements with other methods indicate that coastal fog also occurs throughout the year.

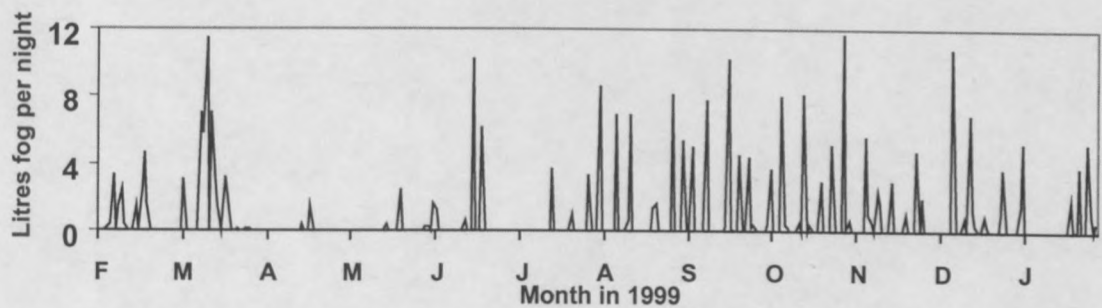


Figure 6.1.3: Daily fog collection with a SFC in 1999 at Vogelfederberg, located 60 km inland from the coast

Coastal fog displays a winter maximum as opposed to the summer maximum seen with inland fog (Nage, 1959 and Henschel et al., 1998). Fog deposition and thus, potential for harvesting, appears to be highest at around 20-30 km from the Namib coast (Hachfeld, in press). It is important that both quantity and quality of fog water be measured from the coast up to 60 km on a long-term basis to facilitate planning of its utilisation.

6.1.3.3 Alternative collectors

Other types of fog harvesters with increased yield and durability are also being tested in the Namib. These include both passive and active fog and general atmospheric moisture collectors. The following experiments have been conducted:

- a prototype developed by Mr. Krumsvik, of Stryn in Norway, uses shredded-paper bricks to absorb air moisture and fog at night and then releases it by evaporation into a condensation chamber when the sun heats the bricks by day;
- different kinds of polypropylene netting tested by Messrs. Coetzee and Mulder of Swakopmund, Namibia;
- cooling system and extractor fan-based prototypes to enhance condensation are being tested by Mr. Shanyengana of DRFN;
- metallic meshes made of oxidation-resistant and wind-durable material tested by DRFN.

The results of the preliminary investigations are promising. The cooling-system and metallic mesh tests yield more fog-water than the polypropylene mesh (Rashel) of equal surface area. Metallic mesh yields 10 – 50% more than the Rashel mesh, and the cooling system-based harvester about 10% more, dependent on the speed at which fog is deposited.

6.1.4 Conclusion

Despite the poor quantity and quality of traditional sources of freshwater in the Central Namib Desert, there appear to be promising opportunities for resolving the water scarcity. Fog is a viable source of water that can be used to supplement traditional sources in rural settlements in this region.

The possibility and implications for water supply to the coastal urban centres are equally great. Dilution of saline groundwater or desalinated water with fog-water, and its use in rural and urban household applications such as gardening are but few of many. However, there is need for research on ways to improve the efficiency of collectors in non-hilly areas, and develop more efficient harvesters. Indeed, this area of research deserves more attention than is currently afforded particularly in fog-occurring low elevation areas as found in Namibia.

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6.2. Exploring fog as a supplementary water source in Namibia (*Fog & groundwater chemistry: mixing for water supply*); Shanyengana, E.S.,^{1,2} Henschel, J. R.,¹ Seely, M.K.,¹ and Sanderson, R.D.².....*Journal of Atmospheric Research*. Accepted

¹*Desert Research Foundation of Namibia (DRFN), Windhoek, Namibia*

²*UNESCO-associated Centre for Macromolecules and Materials, University of Stellenbosch, South Africa*

This publication is a more subject-specific (detailed) version of the paper that was published in the conference proceedings that was selected for publication in a special edition of the *Journal of Atmospheric Research*.

Abstract:

Namibia is an arid country where many rural and urban centres depend on ephemeral rivers for their water supply. These water sources are however, limited and display seasonal salinisation. Fog occurs along the coast and for some distance inland and could be used as a source of drinking water. Data on groundwater salinisation and fog deposition were collected at villages of the indigenous communities and at the Gobabeb Training and Research Centre (GTRC) in the Central Namib Desert. Fog harvesting experiments were conducted with Standard Fog Collectors (SFCs), 1 m² fog screens made from the Raschel mesh used in SFCs and with passive cooling system- and extractor-fan based prototype harvesters. The results indicate that fog occurs throughout the year and that it is of low chemical content. The period of high fog deposition coincides with that of high groundwater salinity and would suit mixing of the two waters to provide water of good drinking quality to people in these areas.

¹ correspondence: cshanyengana@hotmail.com; <http://www.drfn.org/>

Results of fog harvesting with the prototype harvesters indicate that it is possible to increase the efficiency of fog and dew harvesting in existing and other collectors. Fog is a viable source of water in the Namib and could supplement traditional sources in rural settlements and, perhaps also in urban water supply schemes in this region as in other parts of the world where it is used as a source of drinking water.

Keywords: *Namib Desert, fog collection, alternative collectors, groundwater salinisation, fog chemistry*

6.2.1 Introduction

The Namibian coastal region is a hyper-arid environment where sources of freshwater are scarce. Fog occurs on 60 - 200 days per year along the coast and extends for some distance inland. Fog precipitation exceeds rainfall and is therefore a more reliable source of water than rainfall for the desert fauna and flora, and could also be used as a supplementary source of water for human settlements in this area (Lancaster et al., 1984; Pietruszka & Seely, 1985 and Henschel et al., 2000).

The ecological implications and uses of fog by fauna and flora of the Namib Desert have been investigated for some time (Hamilton and Seely, 1976 and Seely et al., 1998). However, investigations of fog collection for water supply to human settlements in the Namib only started in 1995 (Henschel et al., 1998). While it appears that the quantity and quality of fog water make this a potentially good source of potable water, suitable collectors with a durability of several years in the particularly aggressive weathering and windy conditions of the Namib still need to be investigated. These collectors can be adaptations of existing fog collection technology or alternative fog collecting techniques.

This paper presents an overview of the Namibian fog collection programme. It discusses the climatology and chemistry of Central Namib fog and the potential of fog collection for water supply to the coastal urban centres and rural settlements. The paper also discusses preliminary results of fog collection with extractor-fan and cooling-system based prototypes. The latter aims to contribute to research efforts towards development of efficient fog collectors.

6.2.2 Area description, methods and material

6.2.2.1 Climate

Ninety-seven percent of Namibia is arid to semi-arid (Hutchinson, 1995). The central Namib is the most arid part of the country and rainfall is low and highly variable in time and space (Lancaster et al., 1984 and Henschel et al., 2000). Average annual rainfall is 18 mm at the coast at Swakopmund and 21 mm 56 km inland at Gobabeb (Nagel, 1959 and Lancaster et al., 1984). However, it is common to experience consecutive years without rain, for instance, Swakopmund recorded a period of about ten years without rainfall (Nicholson, 1994).

Rainfall decreases along an east–west gradient across the country and is lowest and most variable at the West Coast where fog deposition is highest. Fog occurs regularly in the central Namib. Fog deposition was measured with cylindrical wire meshes (10 cm diameter, 22 cm height) at four sites in the Namib, namely Gobabeb, Ganab, Kleinberg and Vogelfederberg from 1962 to 1996 (Henschel et al., 1998). These sites and others that are designated for fog water collection systems for water supply to local villages and the Gobabeb Training and Research Centre (GTRC) were equipped with Standard Fog Collectors (SFC) in 1997.

6.2.2.2 Constraints to successful implementation of fog collection in the Namib

Topography and nearness to the source of fog are some of the factors to be considered when selecting a site for a fog collection system.

Fog collection systems are preferably located within 5 - 25 km of the fog source, and at an altitude of 400 - 1000 metres above sea level where the highest Liquid Water Content (LWC) often occurs (Schemenauer and Cereceda, 1982 & 1994).

The central Namib is a flat and topographically featureless plain with a slope of 5-8 m per km and extends from the coast to about 200-km inland, at the foot of the Great Escarpment (Henschel et al., 1998). Only a few isolated hills and dunes occur. The area is also frequented by dry mountain winds ('berg winds') with wind speeds of up to 32 m/s (Henschel et al., 1998). These two factors constrain successful implementation of fog collection systems in Namibia. Fog deposition is not particularly enhanced at most sites, and the fog screens are subject to much wear and tear due to the unfavourable wind conditions.

6.2.2.3 The water situation

Urban and rural settlements in the Namib Desert rely mainly on ephemeral rivers for water supply (Jacobson et al., 1995). However, both the quantity and quality of these water resources are impaired by the local hydro-climatic conditions namely, low rainfall and a high rate of evapotranspiration.

Surface water occurs mainly during the rain season and only a small Percent of this water and the direct rainfall infiltrates into groundwater reserves (Jacobson et al., 1995). The groundwater is also subject to seasonal salinisation and is often too saline for domestic use (e.g. Hellwig, 1970 and Shanyengana et al., in preparation).

6.2.2.4 Methods and materials

Fog collection

The potential for fog harvesting at the sites designated for fog collection systems was investigated with SFCs. Preliminary investigations were also carried out with 1 m² fog screens made from a double layer of 35% Raschel mesh, similar to the one used in SFCs', as well as with cooling-system and extractor fan- based collectors, from November 2000 to May 2001 at Henties Bay, on the coast. The cooling system is made of a small refrigeration compressor unit that is mounted with a coil that lines the interior of the covering glass compartment- the collecting surface. The compressor cools the interior of the collector to about -10 C. Fog water is collected on the outside of the cooled glass cover. The extractor-fan collector is made of a suction fan (Donkin series: MAJAX-2, 1440 r/min and FREQ. 50 Hz) housed in an airtight housing with a mesh at the terminus. This system is able to induce a maximum speed of incoming-fog of about 10 m/s over the surface of the mesh- the collecting surface.

Fog and groundwater chemistry

Fog water was collected from October 1996 to October 1997 with SFCs at Gobabeb {23° 34'S; 15° 03'E, altitude 408m above mean sea level (amsl) and 56 km from the sea}, Klipneus (23° 23'55. 9"S; 14° 54'. 07.0"E, 352m amsl and 46 km) and Swartbank (23° 24'S; 14° 54'E, 464m amsl and 37 km). Groundwater samples were obtained monthly from boreholes along the Kuiseb River from September 1998 to September 2000 at the following sites; Homeb (±75km from the sea), Natab 2 (±65km) and Gobabeb (56km). Both fog and groundwater samples were analysed for total dissolved solids (TDS) and major ions. Major ions were determined with an ICP (Inductively Coupled Plasma).

6.2.3 Results and analyses

6.2.3.1 Fog collection

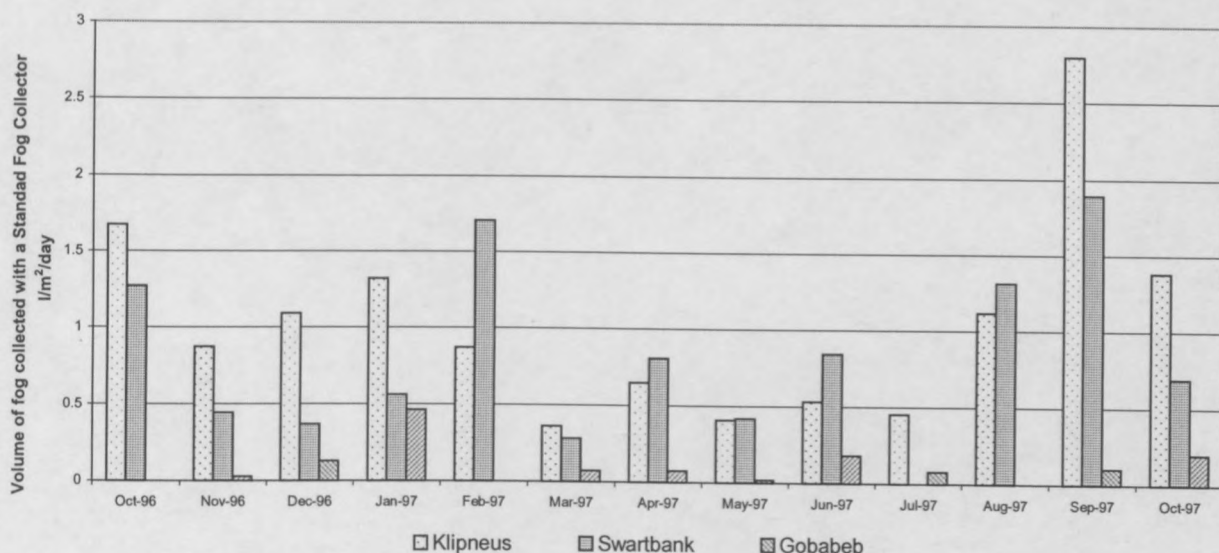


Figure 6.2.1 Daily fog collection at sites of different distances from the coast and elevation- Gobabeb, Klipneus and Swartbank, measured with Standard Fog Collectors.

The results indicate a seasonal variation in fog frequency with most fog occurring from August to February. The daily average fog collection at the test sites was 0.508 l/m²/wet day at Gobabeb, 3.308 l/m²/wet day at Klipneus and 2.390 l/m²/wet day at Swartbank. Fog collection throughout the test period, including days without fog, was 0.104 l/m²/day at Gobabeb, 1.074 l/m²/day at Klipneus and 0.774 l/m²/day at Swartbank (Henschel et al., 1998). No long-term SFC records exist for the coastal area but earlier measurements with cylindrical wire mesh indicate that fog occurs throughout the year. It displays a winter maximum as opposed to the summer maximum seen with inland fog (Nagel, 1959 and Lancaster et al., 1984).

A summary of the results of fog harvesting with the cooling system harvester, its non-cooled controls and with the extractor fan-based harvesters is presented in Figure 6.2.2.

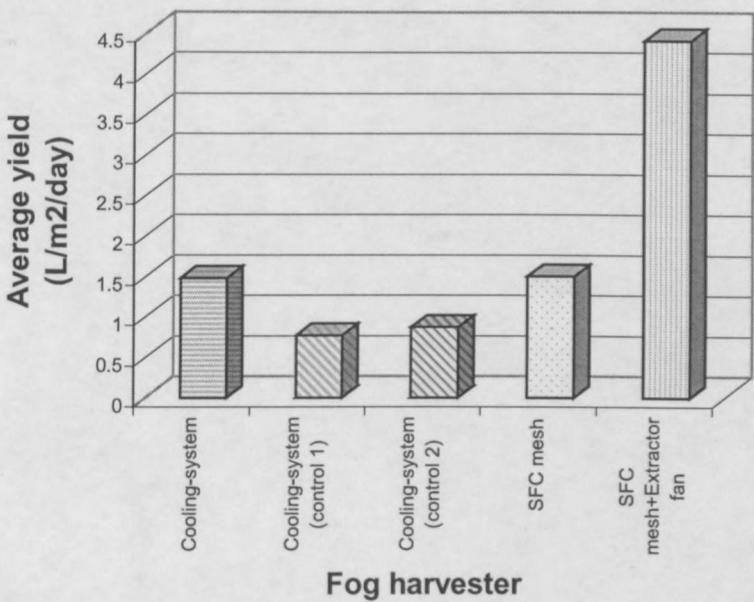


Figure 6.2.2 Fog collection by alternative harvesters and Raschel mesh ('SFC mesh') screens of equal surface area.

6.2.3.2 Fog and groundwater chemistry

Groundwater in boreholes along the Kuiseb river displays seasonal variation in Total Dissolved Solids (TDS), Figure 6.2.3. The variation is characterised by low TDS groundwater during recharge by ephemeral floods and higher TDS during the rest of the year.

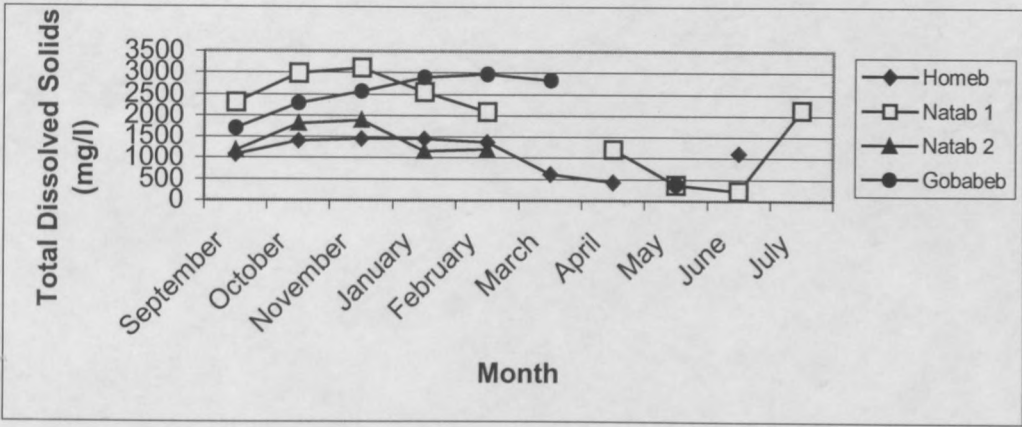


Figure 6.2.3. Groundwater salinisation in boreholes along the Kuiseb River.

Total Dissolved Solids of fog water that was collected at Gobabeb with SFCs during separate fog events, range from 70 - 1000 mg/l, Figure 6.2.4.

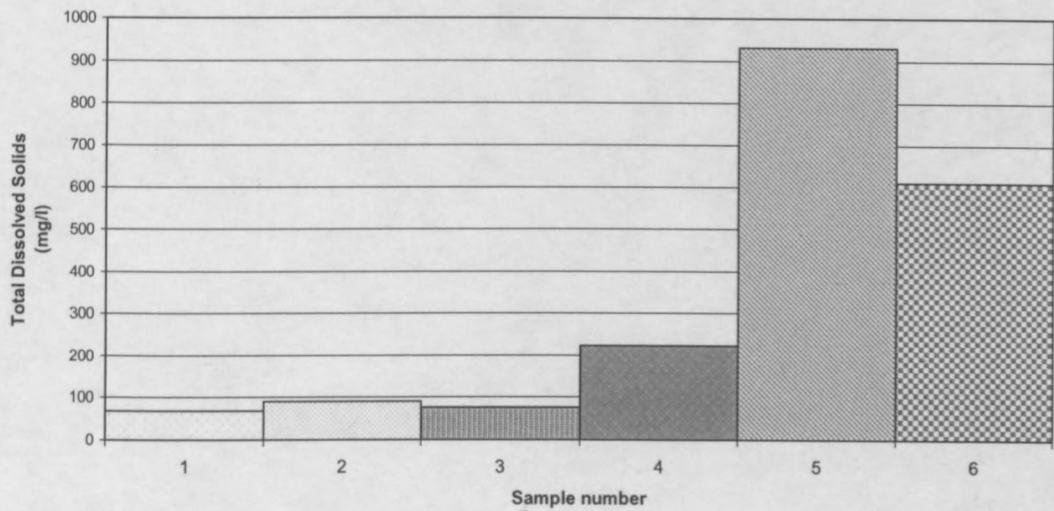


Figure 6.2.4 Total Dissolved Solids of fog water collected during separate fog events at Gobabeb.

6.2.4 Discussion and conclusions

6.2.4.1 Fog collection

Annual fog deposition is more predictable than rainfall and displays a coefficient of variation (CV) of about 41% compared to 133% for rainfall (Seely and Henschel, 2000). Fog deposition exceeds rainfall about seven fold at the coast and two times inland (Nagel, 1959 & 1962; Lancaster et al., 1984; Pietruszka and Seely, 1985 and Henschel et al., 1998). This makes fog a more reliable source of moisture than local rainfall in these areas.

Fog deposition and the potential for harvesting is highest about 30 km from the coast (Lancaster et al., 1984 and Hachfeld & Jurgens, 2000). This area falls within the existing ephemeral river-based urban and rural water supply schemes.

Fog collection by the extractor-fan and cooling-system based collectors generally exceeds that of a passive Raschel mesh of equal surface area. The extractor fan unit collects about three times more fog water than a passive equivalent. The increased yield could be accounted for by a higher fog density per unit area that would be pulled through the collector at higher wind speeds. The latter would increase the amount of fog that goes through the collector at any given time and, as a result enhance interception and collection of fog droplets by the collector. This would also account for the higher yield that is often recorded in SFCs at high elevation areas where fog deposition is found to generally occur at high wind speed (e.g. Schemenauer and Cereceda, 1994).

The cooling system collects almost an equal amount of fog water as a Raschel mesh during fog events. However, an equal and at times slightly lower yield (ca. 70% of the total yield recorded during fog events) is also recorded during days without fog, even at a relative humidity of about 30%. The latter indicates that this type of collector combines both fog and dew collection.

6.2.4.2 Fog and groundwater chemistry

Namib fog is generally of low chemical content and is similar to other fogs reported in less-industrialised areas (Schemenauer and Cereceda, 1992; Eckardt and Schemenauer, 1998 and Olivier, 2001). The fog water is generally of ‘A’ quality, according to the Namibian Drinking Water Quality Standards (NDWQS), Table 6.2.1.

Table 6.2.1. Namibian Drinking Water Quality Standards, DWA (1998)

Determinant	Unit	Limits			
		Group A	Group B	Group C	Group D
		Excellent	Good	Low health risk	High health risk
Conductivity	mS/m	<150	150-300	300-400	>400
TDS	mg/l	<1 050	1 050-2 100	2 100-2 800	>2 800
Sulphate	mg/l	<200	200-600	600-1 200	>1 200
Nitrate	mg/l N	<10	10-20	20-40	>40
Fluoride	mg/l F	<1.5	1.5-2	2-3	>3

The variation in TDS of fog water depends on the cleanliness of the collector surface, which in turn is determined by the level of dust accumulation on the surface prior to fog deposition. Consequently the quality of collected fog water would depend on the frequency of cleaning of the collector surface.

This problem can also be addressed by incorporating a self-cleaning (de-dusting) system on fog collectors, whereby the initial rinse-off water only serves to clean the screen and is thereafter directed away from the storage compartment.

The period of high groundwater salinity at inland sites coincides with that of peak fog deposition, Figures 6.2.1 and 6.2.3, both occurring within the period August to February. This timing of peak groundwater salinity and fog deposition is well suited for dilution of saline groundwater with fog water to provide good quality water for domestic purposes. This is supported by the results of chemical analysis of fog water, Figure 6.2.4 and earlier studies e.g. Eckardt & Schemenauer (1998) that indicate that Namib fog is of low chemical content. Fog water can also be used to dilute semi-desalinated water in urban water supply schemes such as the desalination plant that is planned for the coastal towns. This could have several advantages such as, savings on the total energy input into the desalination works, increased total freshwater output and also that the fog water could contribute towards stabilising the desalinate which is often chemically unstable and as a result, also chemically aggressive.

In conclusion, it appears that despite the poor quantity and quality of traditional sources of freshwater in the central Namib there are possibilities to resolve the water scarcity. Fog is a viable source of water that can supplement traditional sources in rural settlements and perhaps urban water supply schemes in this area. The timing of high groundwater salinity and peak fog deposition is most favourable for dilution of saline groundwater for drinking purposes. Fog collection by fog screens and other collectors can be enhanced, as indicated by experiments with the prototype harvesters. However, there is need for additional research into ways of transferring the lessons learnt from these prototypes to large collectors. There is equally a need to investigate ways of safeguarding the quality of collected fog water.

6.2.5 Acknowledgements

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6.3. Atmospheric moisture collection for water supply: *prototype collectors*;

Shanyengana, E.S.^{a,b*}, M.K. Seely^a, and R.D. Sanderson^b; *Water International (IWRA)*

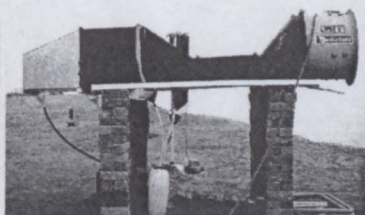
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^a*Desert Research Foundation of Namibia (DRFN), PO Box 20232, Windhoek, Namibia; Fax: +264 (061) 230172;*

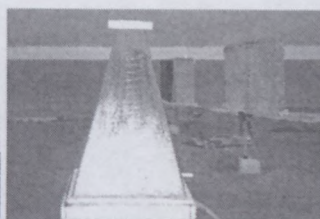
^b*UNESCO Associated Centre for Macromolecules & Materials, University of Stellenbosch, South Africa; <http://www.sun.ac.za>*



Fog-basking beetle of the Namib



Extractor fan collector



Cooling system collector and 1 m² SFC mesh



Water Pyramid

Abstract

Conventional freshwater resources in arid lands are finite and subject to salinization, as a result, access to sources of freshwater is often a source of conflict between people in these regions. This situation demands novel approaches to manage the existing freshwater resources in a sustainable manner as well as to develop new water sources, where such options exist. Atmospheric moisture is in principle an alternative source of potable water for people living in these regions, and its potential for collection and utilisation should be investigated along-side other alternative water sources that are available in these areas. The low efficiencies of current atmospheric moisture collectors are mainly due to a lack of research effort that is put into advancing these systems. This study joins research in other parts of the world that seeks to better the understanding and improve atmospheric moisture collection.

^a * corresponding author: cshanyengana@hotmail.com

Data from experiments with small prototype atmospheric moisture collectors and from investigations of surface properties of fog-harvesting animals indicate that it is possible to enhance the efficiency of existing collectors. This study aims to rally international interest and exchange of information that would help to further the development and utilisation of atmospheric moisture as a source of water. Such research efforts could contribute to improving the quality of life of many people in arid regions worldwide.

Keywords: *arid lands, water, atmospheric moisture, fog and dew collection*

6.3.1 Introduction

Sources of fresh water in arid regions are often impaired by the prevailing hydro-climatic conditions in these regions namely, low rainfall and little replenishment of groundwater (low recharge rates) and a high rate of potential evaporation. Groundwater salinity and salinization in these regions is severe and as a result, freshwater sources become too saline for domestic uses, Walter (1971) (Agnew & Anderson, 1992; Richter & Kreitler, 1993 and Shanyengana, 1997). This water situation demands novel approaches to develop new sources, where possible, and also to manage the existing freshwater resources in a sustainable manner.

Atmospheric moisture is in principle an alternative source of potable water for people living in arid regions, particularly in less-industrialised locations where it is of good drinking quality considering the low atmospheric pollution levels (Schemenauer & Cereceda, 1992; Eckhardt & Schemenauer, 1998, Olivier, 2001 and Shanyengana et al., 2001). This water can be used directly or mixed with existing saline sources to provide good quality water to people that live in these regions.

Anecdotes of successful implementation of collection of atmospheric moisture particularly fog and dew, date as far back as 1500 AD (Schemenauer & Cereceda, 1994 and Baladon, 1995). However, most of the earlier cases are but legends, with little evidence of their efficiency and their contribution to water supply in areas where they existed (e.g. Nikolayev et al., 1995).

This study used passive and active model atmospheric moisture collectors to investigate the feasibility of enhancing the efficiency of existing collectors. The study also looks at some adaptations to fog collection in two beetles of the Namib Desert to see if they have any physical properties that can be of value to man-made fog collectors. Finally, the authors aim to contribute to the understanding of atmospheric collection and also to encourage more research on ways of enhancing collection and use of this water resource.

6.3.2 Background

Arid lands make-up about 34% of the earth's land area, that is 4% extremely arid, 15% arid and another 15% semi arid (Meigs, 1957; Walton, 1971 and Petrov, 1976). Most of these arid lands, particularly the extremely arid ones occur along the west coast of continents in the subtropical latitudes as a result of the aridifying influence of subtropical high-pressure cells and cold ocean currents, and in tropical and temperate zones (Walton, 1971; Petrov, 1976 and Nicholson, 1994). Of interest to this work are coastal fog deserts and hot humid ones where atmospheric moisture is high and could therefor be explored as a source of potable water.

Fog deposition is reported at many coastal location particularly the west coasts of all continents where its deposition and frequency generally exceeds that of rainfall in the arid core of most of these environments (Lancaster et al., 1984; Pietruszka & Seely, 1985; Schemenauer & Cereceda, 1994 and Cereceda et. al., 1996).

The collection of fog for water has long been investigated and involved for instance, using trees as collectors in plantations that are surfaced with plastic sheets as was used in Cape Verde and the Canary Islands. Stone walls were also constructed in ancient towns such as Theodosia, to intercept fog or enhance condensation of atmospheric moisture (Schemenauer & Cereceda, 1994; Baladón, 1995; Gioda et al., 1995 and Nikolayev et al., 1996).

Current fog water supply schemes generally consist of a series of 48m^2 mesh ('fog screens'). These screens are made from a double layer 35% shade coefficient polypropylene mesh or other similar materials in areas where the polypropylene mesh is not available (Schemenauer & Cereceda, 1994b and Olivier, 2001). Such systems are being implemented in most parts of the world and record an average water collection of about $3\text{ l/m}^2/\text{day}$ in Chile; $3\text{ l/m}^2/\text{day}$ in Namibia; $9\text{ l/m}^2/\text{day}$ in Peru and about $7\text{ l/m}^2/\text{day}$ in South Africa (Schemenauer & Cereceda, 1994b; Henschel et al., 1998 and Olivier, 2001).

Justification for alternatives:

Atmospheric moisture is poorly explored as an alternative water resource particularly with regard to large-scale water supply. Knowledge on ways of enhancing its collection in existing collectors and understanding of the effect of varying relevant parameters that could influence the rate of interception or condensation, stand to benefit research towards development of efficient small- and large-scale collectors.

Alternative atmospheric moisture collectors would particularly benefit areas such as the Namib Desert where fog collection with fog screens is proving difficult to implement due to the unfavourable environmental conditions.

Wind storms of about 24 m/s to 32 m/s are frequent and limit successful implementation of fog water supply systems in these areas because they destroy the fog collectors (Henschel et al., 1998).

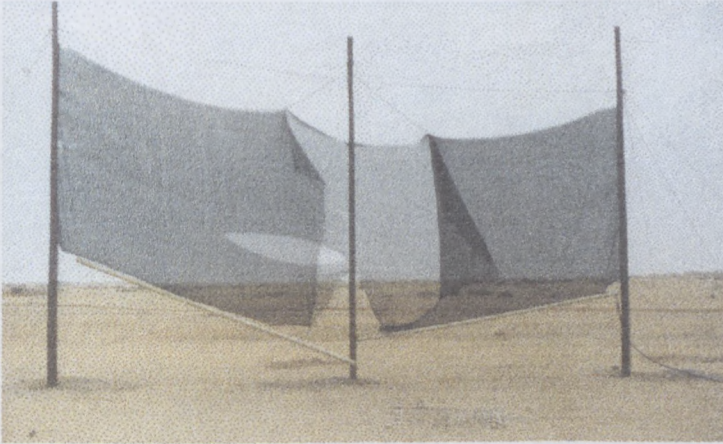


Figure 6.3.1. An example of the effects of frequent windstorms on Fog collectors in the Namib. Such fog collectors have also been witnessed to collapse or tear-up completely during periods of strong easterly winds.

Equally, arid areas further away from the coast record lower or often no fog deposition. However, even these environments particularly hot-humid arid environments present opportunities for tapping atmospheric moisture for drinking water.

6.3.3 Materials and methods

The potential for fog harvesting at any particular site is determined with 1 m² fog screens made from a double layer of 35% rachel mesh, situated 2 metres off the ground- the Standard Fog Collector (SFC) as described by Schemenauer & Cereceda (1994b). Experiments were conducted with 1 m² fog screens made from the SFC mesh and 40% (Indoor) aluminet shade cloth- aluminium-coated HDPE (High Density Polyethylene) fibres as well as with cooling system- and extractor fan- based collectors in the Namib Desert between 2000 and 2001. Experiments with absorptive material (Water Pyramid) were conducted under similar climatic conditions in 1998.

The cooling system collector is made of a small refrigeration compressor unit that is mounted with a coil lining the interior of the covering glass compartment- the collecting surface, Figure 2.11. The compressor is able to cool the interior of the collector to about -10 C. Fog and general atmospheric moisture is collected on the outside of the cooled glass cover. The Water Pyramid is of equal surface area as the cooling system collector. The pyramid is opened at night and fog and/or general atmospheric moisture is absorbed onto shredded paper that is packed inside the instrument. The glass covering is shut during the day and water that is absorbed onto the paper evaporates, condensing on the interior of the glass covering from where it is channelled into a receiver.

The extractor-fan collector is made of a suction fan (Donkin series: MAJAX-2, 1440 r/min and FREQ. 50 Hz) housed in an airtight housing with a polymeric mesh at the terminus, the collecting surface, Figure 2.9.

This system is able to induce a maximum speed of about 10 m/s over the surface of the collector. The experiments were either conducted through a whole fog event (one fog day) or at times only for as long as it was required to obtain a measurable yield. Readings were also taken at varying relative humidity and internal & external temperatures (in the case of the cooling system collector) in order to determine the effect of varying these parameters.

Fog harvesting beetles ('fog-basking beetle') of the species *Onymacris unguicularis* and *Onymacris bicolor*, 10 individuals from each species, were collected in the Namib Desert and contact angles on their cuticles were determined. The contact angles were determined with the Cahn Instruments' DCA-322 (Cahn Dynamic contact angle Acquisition).

6.3.4 Results and discussion

6.3.4.1 SFC mesh (Raschel mesh) and Aluminet shade cloth

Figure 6.3.2. shows that fog collection with the SFC mesh is similar to earlier findings in the Namib environment (Henschel et al., 1998). However, the aluminium coated mesh (Aluminet) collects on average $96\pm22\%$ of the fog yield of the un-coated polypropylene that is used in the SFC.

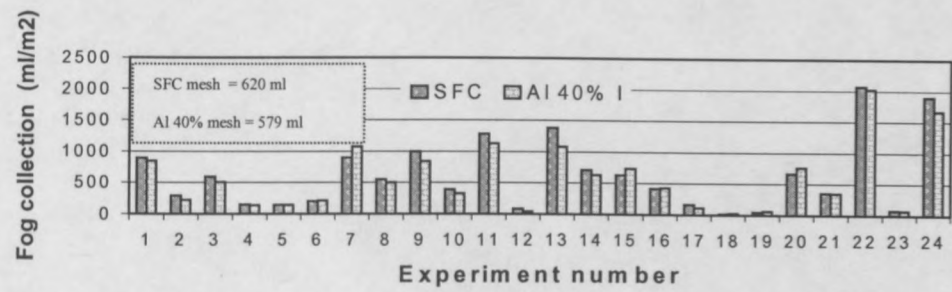


Figure 6.3.2. Fog collection in a 1 m² SFC mesh and Aluminet 40% I collector.

Fog collection in either collector increases with the speed of fog-bearing wind and vice versa. The higher yield recorded in the SFC mesh can be accounted for by the difference in percentage shade coefficient in the different meshes, the 35% SFC one being more conducive for fog collection than the 40% Aluminet (e.g. Schemenauer & Cereceda, 1994b).

The aluminium coat that is on the Aluminet HDPE strands imparts a 'metallic' finish on this collector. This coat enables the collector to collect dew, in addition to intercepting fog. The contribution of dew to the total yield is minimal and thus, rather insignificant during high wind speeds when fog collection is highest.

However, it does become significant during periods when fog deposition is accompanied by low wind speeds. This quality of Aluminet mesh makes a 35% shade coefficient mesh a more appropriate collector material for low elevation areas where fog deposition generally occurs at low wind speed (e.g. Schemenauer & Cereceda, 1994).

6.3.4.2. *Extractor fan- based collectors (active) and passive collectors*

The potential for fog collection is generally higher in high elevation areas than in low elevation ones mainly due the high wind speed experienced in the earlier locations (Schemenauer and Cereceda, 1994a & c). This understanding of fog deposition is always incorporated into the selection criteria for a site for a fog water supply system by siting such system on higher ground, that is, if such exist in the area envisaged for implementation (Schemenauer & Cereceda, 1994c). The situation in some low elevation areas such as in most parts of the Namib Desert fog zone does not present such topographic features and would thus benefit from other means of enhancing fog collection.

Preliminary experiments with fog collectors mounted on a moving vehicle indicate that the amount of collected fog water varies depending on the speed at which fog is forced to go through the collector- by driving at varying speed. Subsequent trials with an extractor-fan based collector that could induce a speed of 10 m/s indicate that it is possible to increase fog collection in a Rachel mesh up to three fold, Figure 6.3.3.

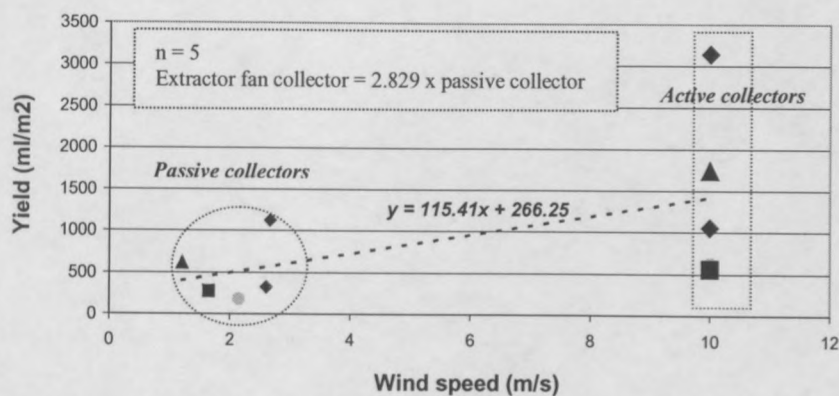


Figure 6.3.3. Fog collection in an extractor fan- based Rachel mesh collector (active collector) and a passive one of equal surface area

The increase in fog collection would depend on the speed induced by the extractor fan and could mean that an even higher increase in fog collection is possible. Increasing the wind speed would also affect how much fog is forced through the collector and it might be beneficial to also increase the percent shade coefficient of the collector. That is, a higher percent shade coefficient (smaller openings) would accompany an increased wind speed.

Larger collectors such as the 48 m² ones used in most fog collection schemes would require large and more expensive extractor fan motors and could thus be uneconomical, depending on how much fog they collect, and for what end-uses. However, much cheaper alternatives could also be considered, such as attaching a wind vane behind the collector or designing the collectors such this act as a wind tunnel. Such systems, particularly the combination of the optimal location and extractor fan-type device could improve fog collection in both high and low elevation sites.

6.3.4.3. *The water pyramid and cooling system*

Figures 6.3.4 a & b and 6.3.9 show that fog collection in the water pyramid is lower than in the cooling system and its non-cooled controls. However, the inventor indicates that a 3.8 metres pyramid would yield about 250 litres of fresh water per day.

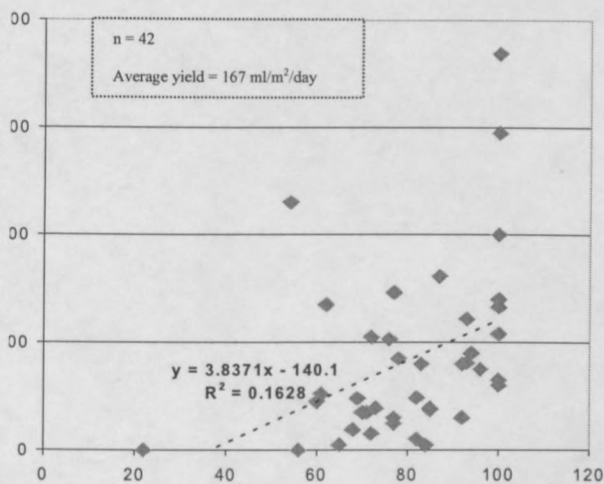


Figure 6.3.4a) atmospheric moisture collection by the Water Pyramid

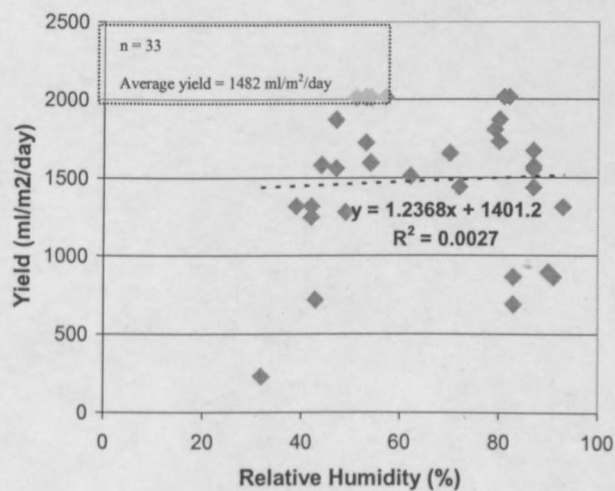


Figure 6.3.4b) Collection in the cooling system collector

The low yield recorded in the water pyramid could be explained by the fact that this system involves too many processes. Firstly intercepting and then absorbing the collected moisture onto shredded paper, and then afterwards evaporating the water that is absorbed and then re-collecting it as the end-water. Each step would incur losses that are otherwise avoided in 'single-phase' collectors such as the cooling system where the collected moisture runs-off directly into the reservoir.

The cooling system collector yields an amount equal to that of a SFC mesh of equal surface area during fog events, however, it maintains an almost equal amount even during period when there is no fog up to a relative humidity of about 40%. Figure 6.3.5 shows that fog collection in the cooling system is not only a function of the relative humidity but rather the relative humidity and the outdoor temperature.

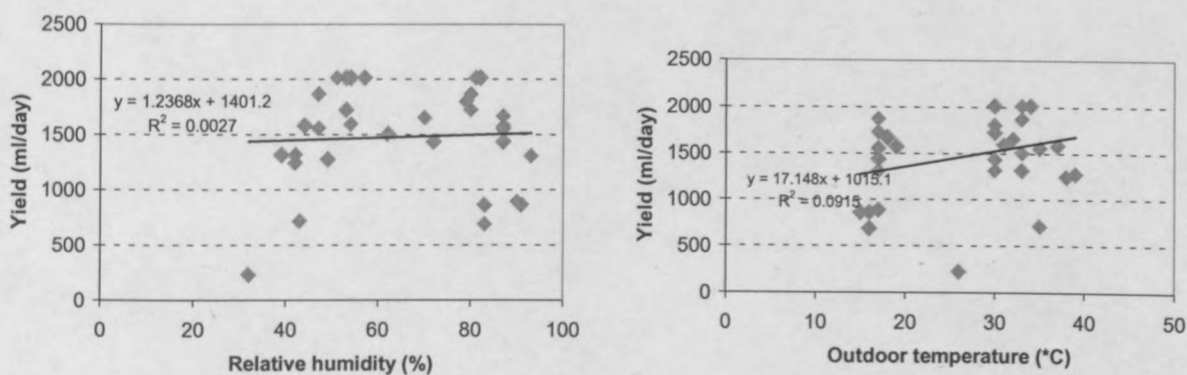


Figure 6.3.5. Graphs showing the relation between moisture collected by the cooling system (yield), the Relative humidity and outdoors' temperature.

The graphs indicate that the yield is generally high during periods of fog deposition, that is, when the relative humidity is 100%. This yield is still maintained even when the relative humidity is 40%, and particularly during periods when the outdoor temperature is high.

This is because the cooled collector surface induces a thermal gradient that enhances condensation and collection of atmospheric moisture. This thermal gradient would be more pronounced in hot-humid locations such as the coastal arid areas of the Southern Coasts of the Red Sea and Persian Gulf (Amiran & Wilson, 1973).

6.3.4.4. *Fog collection and surface properties of natural harvesters*

Water is a primary limiting factor and 'environmental stress' of predominant importance in arid environments and natural selection is expected to favour adaptations that optimise its acquisition and/or conservation in organisms that inhabit these areas (e.g. Rundel, 1978 and Cloudsley-Thompson & Lourenço, 1994). Organisms in these environments engender morphological, behavioural and physiological adaptations to acquire and conserve moisture (Noy Meir, 1974; Hamilton & Seely, 1976; Lundholm, 1976; Rundel, 1978; Seely, 1979; Seely et al., 1982; Nicolson, 1990 and Cloudsley-Thompson & Lourenço, 1994).

The results of contact angle analyses in the fog-basking beetles, *Onymacris unguicularis* and *Onymacris bicolor*, indicate that their un-wetted surfaces (advancing angle) are more hydrophobic (ca. 90°), Figures 6.3.6a & b.

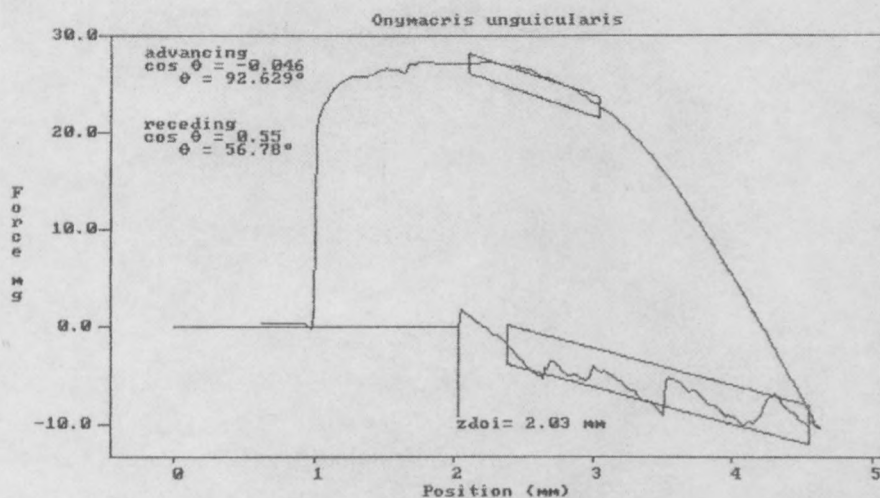


Figure 6.3.6 a. Contact angles of the cuticle of *Onymacris unguicularis*

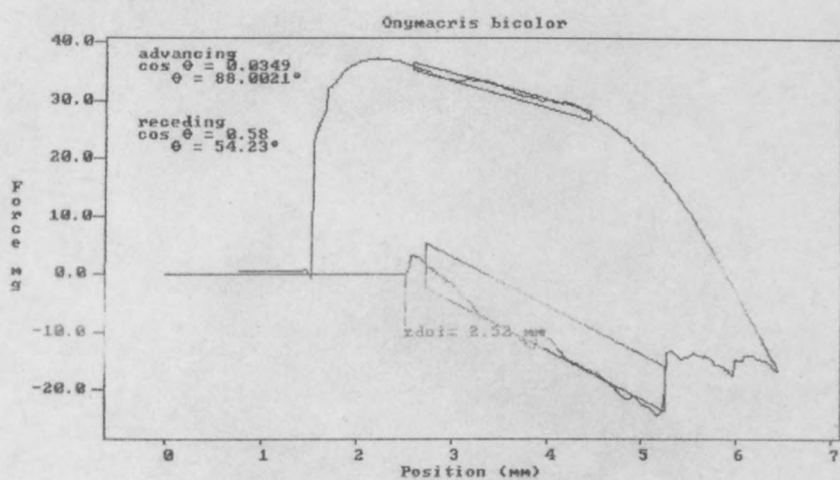


Figure 6.3.6 b. *Onymacris bicolor*

These surface conditions enhance formation and runoff of large water droplets as opposed to film formation, which occurs in the case of hydrophilic surface conditions (e.g. Cytonix, 1997), Figure 6.3.7.

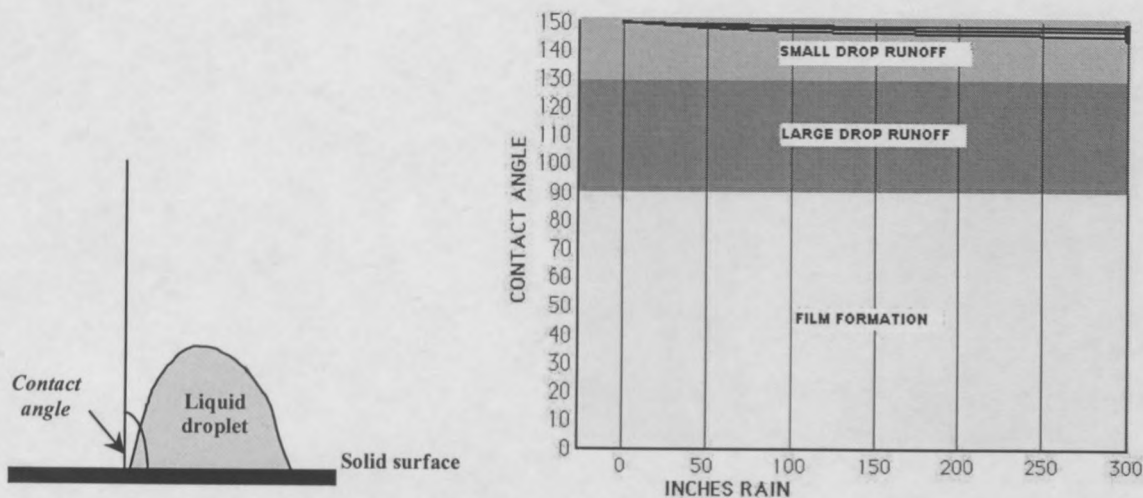


Figure 6.3.7. Contact angle interpretations (Source: Cytonix, 1997)

The high contact angle formed between the surface (cuticle) of the beetle and the fog droplet increases the water repellence of the surface and thus, enables the droplet to roll freely to the beetle's mouthparts. Such a surface is not beneficial to the beetle during high wind speeds because most of the fog that is collected on the surface will be blown away, however, they are suitable in low elevation areas such as the Namib where the speed of fog-bearing wind is low. Fog-basking beetles have been noted to cease fog-basking activities and burrow into the sand as soon as the winds speed increases (Seely, 1979).

These physical properties have direct applications to atmospheric collectors such as fog screens. Analyses of the contact angles of polypropylene fibres used in fog collectors indicate that these are less hydrophobic. These fibres could be made more hydrophobic by polishing them with commercially available hydrophobic coats or exudates, Figure 6.3.8

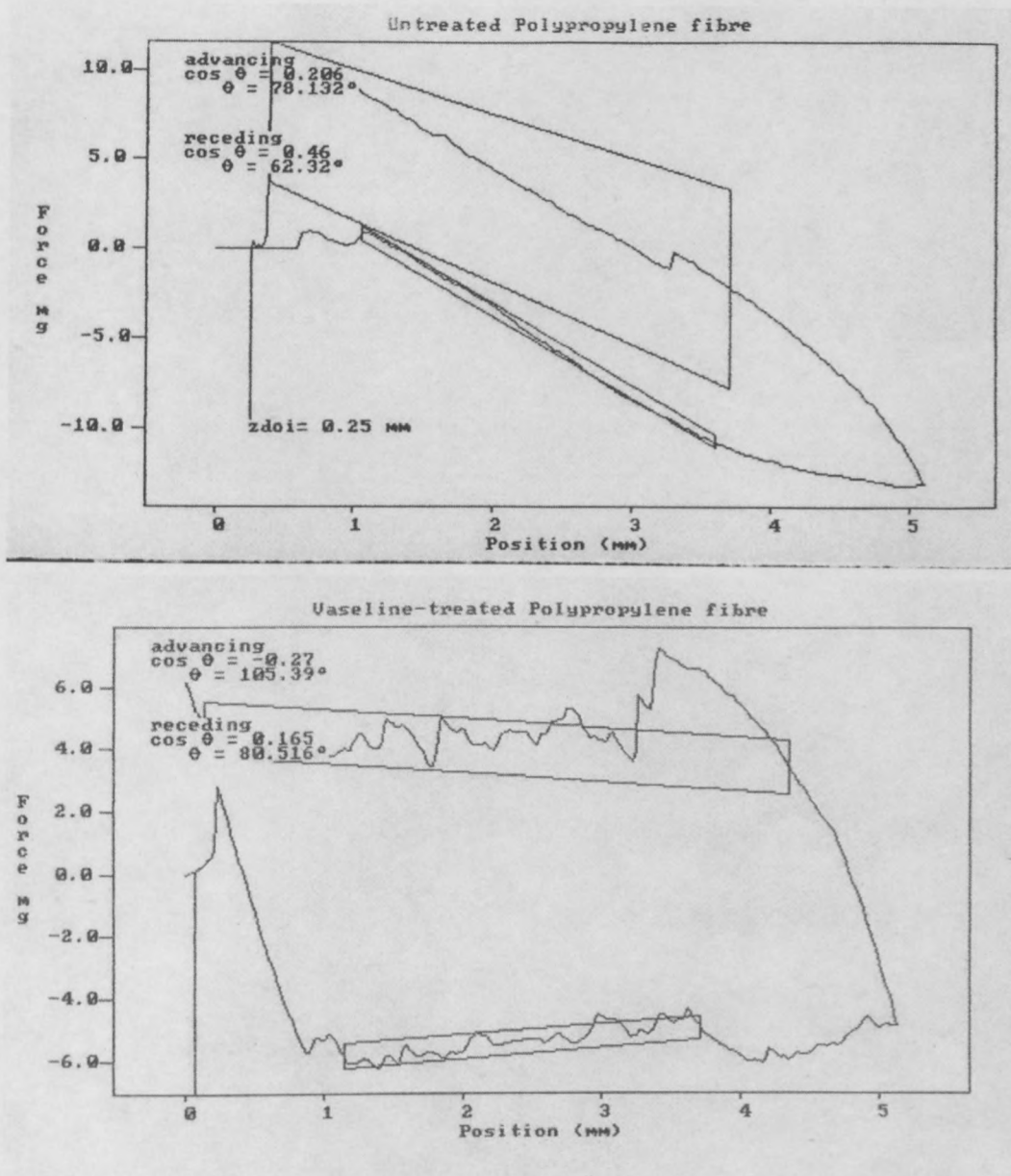


Figure 6.3.8. Un-treated (above) and vaseline-treated fog collector fibres (polypropylene)

These coats could also prove useful when considering other types of collectors. One such an example is for instance that a larger cooling system collector in a low elevation area would be more suited by a hydrophobic collector that would enhance runoff of the collected moisture.

6.3.5. The way forward

There is compelling evidence that it is possible to enhance collection of atmospheric moisture in water supply schemes as exist today in arid regions. However, the actual implementation of most of the above-mentioned possibilities requires further research efforts with the aim of generating economically viable options. Research and development efforts are needed into ways of improving the efficiency of atmospheric collectors, particularly to develop more cost-effective schemes along the concepts of the extractor-fan based collector, Figure 6.3.9.

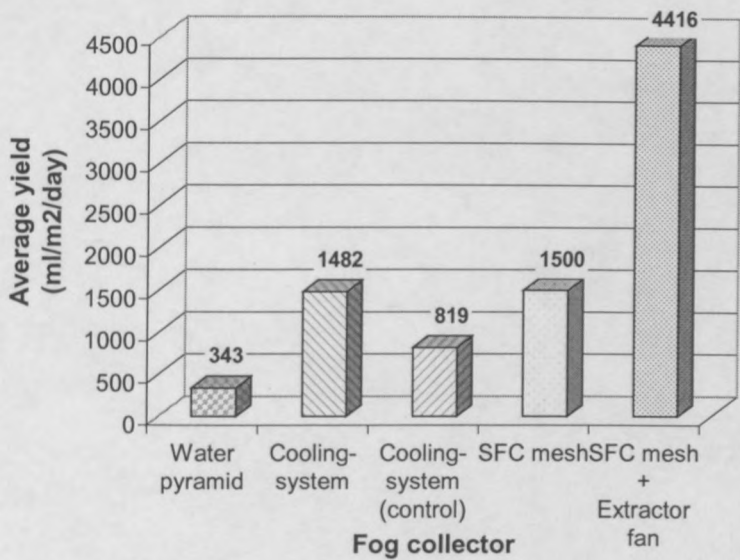


Figure 6.3.9. Average daily fog collection in the different collectors

A combined fog collector, made of the extractor-fan and cooling system collectors appears promising because not only would the collector perform better during fog events but also in conditions of much lower relative humidity. The efficiency of such a collector, as with all other passive collectors discussed previously, is expected to display an exponential increase with increasing surface area of the collector.

This is because a larger collector would imply a wider spread of the suction or cooling effect that it creates and as a result, a more pronounced regional effect on the movement of the moisture.

Other smaller experiments that were carried out during the course of the study include trials with electrified fibres to collect fog water. It was assumed that fog droplets are attached to condensation nuclei (mainly dust particles) that would respond to a charged collector surface. These experiments did not yield positive results and it could be because the fog collectors used were too small (0.25 m^2) to effect any significant influence that is necessary to increase fog collection. A much larger collector surface and perhaps a higher voltage than the 8 volts that was used could be more effective.

Efforts elsewhere to develop atmospheric moisture collectors are also underway. One such example is the refrigeration system "VEIZAR water generator" that was developed by *Euro-frigor Ingeniería Frigorífica S.L.* in Spain (Berruezo, 1997). This system is able to collect about 10 to 50 litres of water per hour, depending on the relative humidity. This system and a few other innovations are still too expensive and therefore, not cost-effective to implement, mainly due to the high-energy consumption, however, these are all encouraging steps towards development of efficient systems that need to be encouraged.

6.3.6 Conclusion

Atmospheric moisture is a potential source of freshwater for arid environments that should be investigated alongside alternatives such as seawater and groundwater desalination. The efficiency of current atmospheric moisture collectors falls well below that of other alternative water supply systems but this is mainly because very few research efforts have been put into advancing this technology.

International exchange is required to further knowledge in this field, particularly to investigate and design more economically viable options. Such research efforts stand to benefit many people in arid regions by improving provision of water to areas where the current sources of freshwater are either of poor quality, too dependent on expensive and unsustainable water transfers or simply inadequate. Indeed, research in this area could contribute to improving the quality of life of people in arid regions.

6.3.7 Acknowledgements

We thank the Spanish Embassy in Namibia for funding construction of the equipment used in the study, and the University of Namibia for logistic support during fieldwork at its Henties Bay Campus. We are equally grateful to RUDREF Refrigeration & Air conditioning of Walvis Bay; Namib Windows, Swakopmund; and Starke Aircon & Refrigeration, Windhoek, for assistance with acquiring material and assembling the model fog collectors at a reduced cost.

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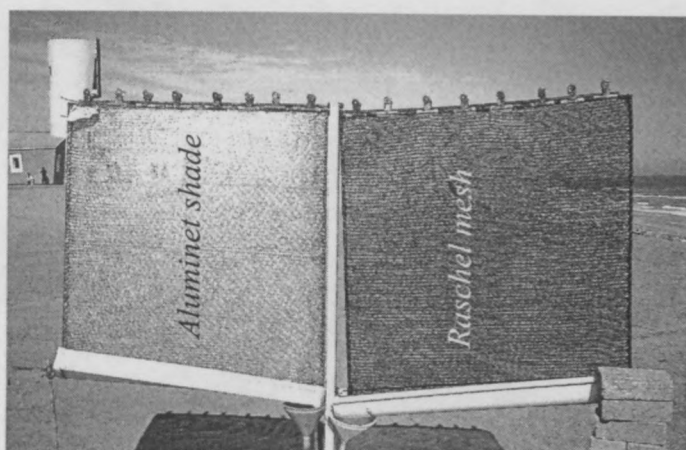
6.4. Testing greenhouse shade nets in collection of fog water for water supply;

Shanyengana, E.S.,^{1,2} Sanderson, R.D.,¹ Seely, M.K.,² and Schemenauer, R.S.³ ; *Journal of Water Supply Research & Technology- AQUA (IWA)* Submitted

¹UNESCO Associated Centre for Macromolecules and Materials, University of Stellenbosch, South Africa

²Desert Research Foundation of Namibia (DRFN), P.O. Box 20232, Windhoek, Namibia

³Atmospheric Environment Canada. Toronto, Canada.



Abstract

Fog is an important source of water for some inhabitants of arid regions where other sources of freshwater are scarce. Fog collection was carried out with polymeric greenhouse shade nets in order to investigate the feasibility of using similar shade cloths in fog water supply schemes in areas where the Raschel mesh that is used in Standard Fog Collectors (SFC) is not available.

² E-mail: cshanyengana@hotmail.com; Fax: +264 (061) 230172

The fog collectors were made from the Outdoor and Indoor Aluminet greenhouse shade nets of varying percent shade coefficient. The Indoor weave is similar to that found in the Rachel mesh that is used in SFCs' and proves to be more suitable for fog collection than the Outdoor one.

Fog collection with collectors made from the Indoor weave mesh of varying percent shade coefficient indicate that the 40% shade coefficient is more appropriate for fog collection than the 60% and 90% mesh. The Aluminet collectors appear to combine both fog and dew collection. The latter would make a 35% shade coefficient Aluminet ('metal'-coated) collector more efficient than the plain polypropylene mesh that is used in fog collectors, particularly in low elevation areas where fog deposition is lower and the contribution of dew to the total collected volume is a significant one.

The results of this study would enable intended users of fog water to select the right weave and percent shade coefficient of a given mesh that is to be used for fog collectors in areas where the Raschel mesh is not available.

Keywords: *Water supply, fog collection, greenhouse shade net, Standard Fog Collector (SFC)*

6.4.1 Introduction

Fog is a key source of water for some people in arid regions (Schemenauer & Cereceda, 1994a). Fog water in these areas is of good drinking quality and is mainly collected with collectors that are made from a special weave and percent shade coefficient polypropylene mesh (see detailed description in Background section; Schemenauer & Cereceda, 1994b).

The particular fog collector material is at times not available in some parts of the world and as a result, it often limits implementation of fog collection in these areas (Mac Quarrie, 2001 and Olivier, 2001). Other types of mesh such as greenhouse shade nets with weave and percent shade coefficient properties close to those found in the SFC's Raschel mesh are often found in some of these areas.

This paper discusses results of fog collection with the Aluminet shade net. Experiments were conducted with fog collectors made from the two weaves and various percent shade coefficients of the Aluminet mesh that are available in Namibia and South Africa in order to determine the most appropriate one for use in fog collectors. All of the experiments were conducted alongside a Raschel mesh in order to determine the relation of the Aluminet collectors to the earlier.

6.4.2 Background

Fog collection for drinking water purposes continues to receive increasing attention, particularly in arid regions where the availability of freshwater is limited. A well-renowned case of fog collection is a Chilean village, Chungungo, where fog water has been collected to meet the water demand of its about 300 plus residents since 1992 (Schemenauer & Cereceda, 1994a). Fog collection has since then been implemented throughout the world with one of the most recent examples being in a small community, Lepelfontein, in South Africa (Rautenbach & Olivier, 2001).

Fog water collection schemes generally consist of a series of 48 m² collectors. The collector is made from a double layer 35% shade coefficient polypropylene mesh that covers approximately 60% of the surface area of the collector (Schemenauer & Cereceda, 1994b). These collectors record an average fog collection of about 3 litres /m²/wet day at the above-mentioned Chilean site, 9 l /m²/wet day in Peru, 30 l/m²/wet day at sites in Oman, 3 l/m²/wet day in Namibia, and about 7 l/m²/ wet day in South Africa (Schemenauer & Cereceda, 1994a; Henschel et al., 1998 and Rautenbach & Olivier, 2001).

The potential of a site for a fog water supply scheme is determined with a SFC (Schemenauer & Cereceda, 1994b). The 1-m² collector is made from the same material that is used in the larger collectors and is used to provide preliminary data on the quantity of fog water that can be collected by a fog water supply scheme. The use of a SFC also allows for comparison with other areas, throughout the world, where fog collection is being investigated.

6.4.3 Methods

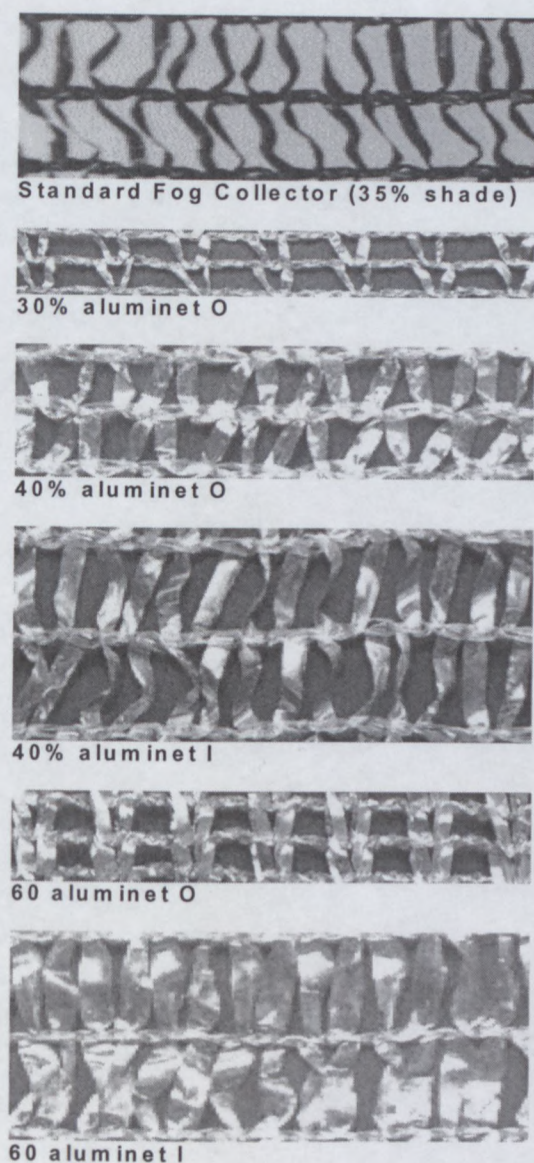


Figure 6.4.1. Single layers of various meshes, showing the weave and percent shade coefficient.

Fog collectors were made from Raschel mesh and from Aluminet shade nets that

are both available in similar sizes and are of comparable cost per square meter.

Most of the experiments were carried out along the coast of Namibia, at Henties Bay, and the remainder were conducted about 60-km inland, at Gobabeb.

Aluminet shade is made of High-Density Polyethylene (HDPE) strands (Polysack, 2001). The strands are coated with aluminium in order to increase their reflectivity and thus, ability to keep greenhouses cool during the day. The mesh is available in two weaves namely, Aluminet *O* (Outdoors) & *I* (Indoors), and at percent shade coefficients of 30, 40, 50, 60, 70, 80 and 90 (Polysack, 2001). Samples of some of these nets are presented in Figure 6.4.1.

Fog collection was done with collectors made from Outdoor & Indoor Aluminet 40% mesh. The effect of varying the

percent shade coefficient was investigated with double layers of the 40%, 60% and 90 % Indoor mesh. The collector with the highest yield was then operated alongside a Raschel mesh for a period of about 4 months in order to determine its relation to the latter.

The use of a Rachel mesh alongside all the experiments enables comparison of the different collectors even when data was obtained during separate fog events and varying climatic conditions. In the latter, a yield ratio (i.e., yield of Aluminet collector to yield of Raschel mesh collector) is used. Most of the experiments were conducted through an entire fog event (one fog day), however; sometimes they were only operated for as long as it was required to obtain a measurable yield.

This experiment design made it possible to collect more data points as was required to enable comparison of the collectors.

6.4.4. Results and discussion

The results of fog collection by the different weaves indicate that the Indoor weave collects more fog water than the Outdoor one, Figure 6.4.2.

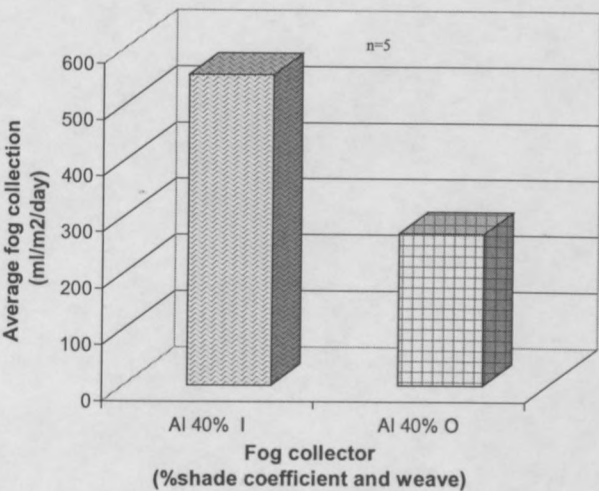


Figure 6.4.2. Average fog collection in Aluminet 40% collectors of Indoor (I) and Outdoor (O) weave

The Indoor weave is in the shape of an isosceles triangle and resembles the weave found in the Raschel mesh while the Outdoor weave has a shape of an equilateral triangle, Figures 6.4.1 and 6.4.3.

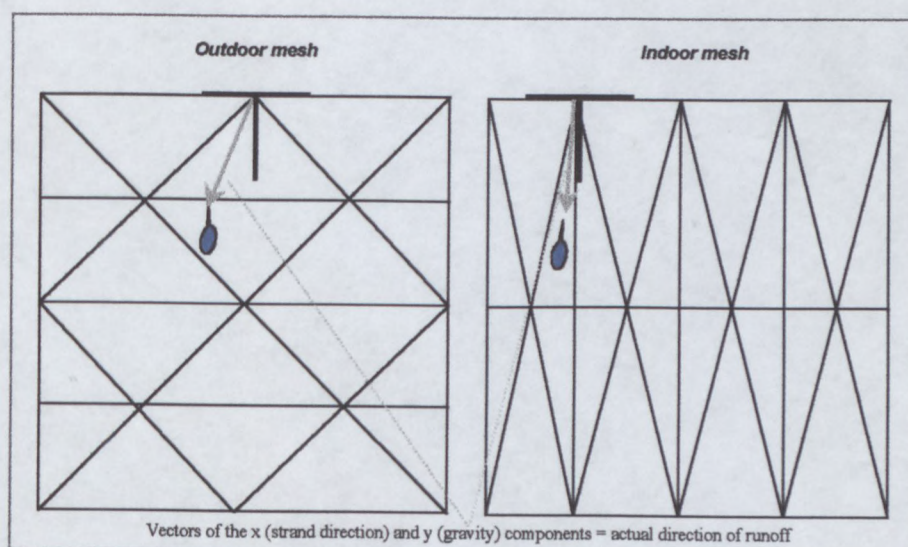


Figure 6.4.3. A schematic view of the weave in the Outdoor and Indoor Aluminet mesh of equal Percent shade coefficient

The strands in a mesh with an Isosceles triangle weave are more close-packed (i.e., the triangle is narrower) and near vertical. The Indoor strand arrangement has a near vertical vector of the flow of collected droplets that enhances coalescence of the droplets and a more voluminous runoff on the strand in this weave than in the Outdoor one. Runoff on the strands of the Outdoor weave has a more horizontally oriented flow vector and therefore the runoff is slower and more droplet-wise than in the Indoor weave. As a result, a collected droplet on a strand in the Outdoor weave mesh is more susceptible to dropping off the strand or to being blown away in the wind that accompanies fog deposition. The latter accounts for the relation that is observed in Figure 6.4.2.

Fog collection in collectors made with the Indoor weave mesh of varying percent shade coefficient is highest in the 40% collector and decreases with increasing percent shade coefficient, Figure 6.4.4.

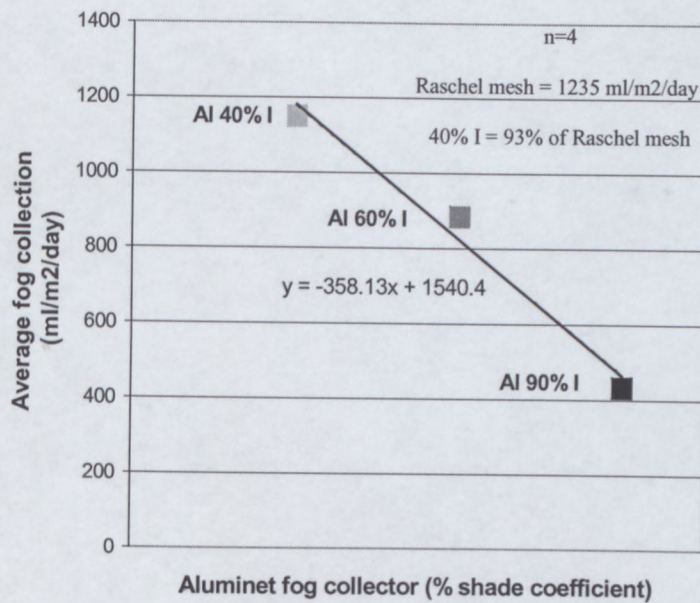


Figure 6.4.4. Average fog collection in Indoor Aluminet collectors of varying Percent shade coefficient

This pattern can be attributed to an increase in the shielding-effect of the mesh that results from the increase in percent shade coefficient of the collector. The degree to which incoming fog is diverted would depend on the shielding effect of the mesh, that is, the higher the percent shade coefficient the higher the diversion and as a result, the collector yields a smaller volume. This indicates that it is necessary that some through-flow be permitted, so that the collector does not act as a shield, which would otherwise force most of the in-coming fog to divert and flow sideways. It should, however, be noted that earlier work on the Rachel mesh indicates that 35% is the optimal shade coefficient for fog collection, and also that the linearity of the relation presented in the graph only serves to show the relation between these three points and would not suffice to accurately predict fog collection in a higher or much lower percent shade coefficient because that would require more than three data points to be statistically acceptable.

The 40% Indoor collector is best among other Aluminet collectors and yields on average 96% (range = 50 - 164%) of the fog collection of a Rachel mesh, Figure 6.4.5.

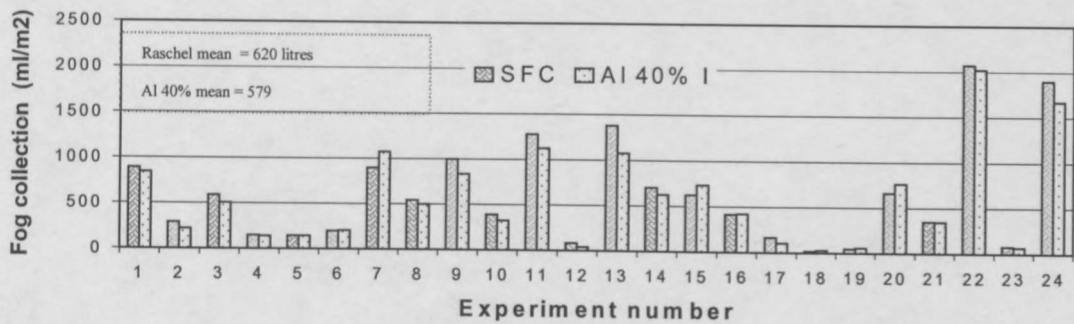


Figure 6.4.5. Fog collection (daily and hourly) in the Raschel mesh and Aluminet 40% I collectors

Cases where fog collection in the Aluminet collector approaches the 96% average or where it is higher than that in the Raschel mesh occur mainly during periods when fog deposition happens at low wind speed, Figure 6.4.6.

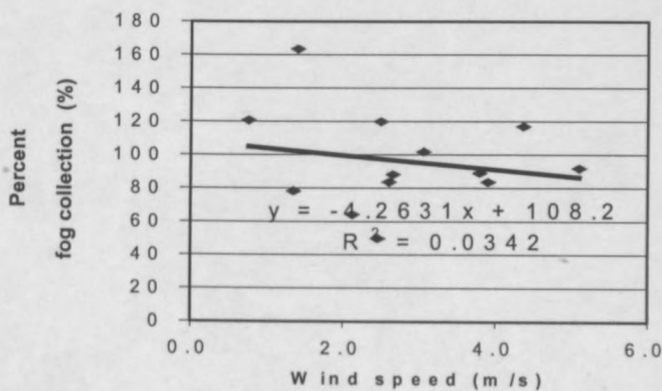


Figure 6.4.6. Fog collection in the Indoor Aluminet 40% collector expressed as a percent of fog collection in a Raschel mesh of equal surface during different speeds of fog deposition.

The increased yield in the Aluminet collector could be attributed to the collection of dew that would be higher on the relatively cooler aluminium coated fibres than on the polypropylene ones of the Rachel mesh. The data set is, however, too small to substantiate this opinion as reflected by the r^2 value of only 0.03 and therefore, more experiments would be necessary to confirm this possibility.

The contribution of dew to the total yield is minimal and thus, rather insignificant during high wind speeds when fog collection is high, however, it becomes significant during periods when fog collection is low, as happens during low wind speeds. The latter makes aluminium/metal-coated netting attractive for construction of fog collection systems in low elevation areas where fog deposition generally occurs at low wind speed. Use of a 35% percent shade coefficient Aluminet mesh, i.e., one similar to the well-tested Raschel mesh (e.g. Schemenauer & Cereceda, 1994b) could possibly yield better results than the 40% one that is used in this study.

This study only serves to point out the feasibility of using other material for fog collectors and also to aid intended users of fog water with the selection of netting. The actual implementation of fog collection with Aluminet nets or other material should always include analysis of the quality of the collected water to ensure that the collector does not impart any chemicals that would pose a threat to the health of the users. The latter particularly applies to Aluminet shading considering that Aluminium is one of the main elements associated with Alzheimer's disease. The evidence for Aluminium and Alzheimer's is still circumstantial, however, it emphasises the importance of choice of collector material and occasional water quality monitoring in fog water supply schemes.

6.4.5 Conclusions and recommendations

This study shows that other greenhouse shade nets can be used for fog collection, particularly in areas where the polypropylene mesh that is used in SFCs is not available. Mesh with an isosceles triangle-like weave and a percent shade coefficient of about 35 - 40% are more suitable for fog collectors than ones with a more equilateral triangle shaped weave or with a higher percent shade coefficient.

The results of this study would enable intended users of fog water to select the right weave and percent shade coefficient of a given mesh that is to be used for fog collectors in areas where the Raschel mesh is not available.

6.4.6 Acknowledgements

We thank The University of Namibia for the logistic support it rendered during fieldwork at its Henties Bay Campus. We are also grateful to Mrs. Moizelle Dahl and Mr. Vilho Mtuleni of the Desert Research Foundation of Namibia, who assisted with acquiring the Aluminet shade nets and with data collection, respectively. Dr. Joh Henschel of the Desert Research Foundation of Namibia and Ms. Annabel Smith, a student at Royal Holloway University (Britain) assisted with editing the manuscript.

6.4.7 References

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CHAPTER 7: SUMMARY OF THE THESIS RESEARCH FINDINGS

CHAPTER 7: SUMMARY OF THE THESIS RESEARCH FINDINGS

This thesis is based on publications that emanated from the research of this study, of which one was published in the proceedings of the international conference on fog and fog collection that was held in Canada in July 2001, and the remainder have been submitted to the listed scientific journals. This chapter summarises the conclusions and recommendations of all the publications and also serves to highlight the contributions of this thesis to new knowledge on groundwater chemistry and supplementary sources of freshwater in arid environments.

7.1 Summary of Discussions and Conclusions

7.1.1 Hydrochemistry

Groundwater in arid environments is generally accepted to be very saline due to the low rainfall and low rate of recharge in these areas. The seasonality of this salinity is, however, poorly investigated particularly in arid regions that have ephemeral (seasonal) surface flow. It is often assumed that these regions have an abundance of freshwater, that is, even after the flood events there is still a lot of potable groundwater. This study shows that Groundwater in these type of ephemeral river sources in arid parts of Namibia namely, the Namib Desert and the Cuvelai delta in North central Namibia (depth 10 - 23 meters) display seasonal variation in Total Dissolved Solids (TDS) and chemical composition. The lowest TDS values are recorded during the rainy season, that is, after rains in the high rainfall areas and only after flood events in the lower rainfall areas.

The TDS in individual water sources generally varies from about 145 mg/l to 11 000 mg/l in response to recharge (*refreshing*) by rain and surface flow; concentration by evaporation; dissolution of saline sediments (mainly evaporites); and by mixing or pumping-induced intrusion by deeper, more saline water, Figure 7.1. Groundwater salinization in both sites is generally characterised by chemical evolution from Na- and Ca (HCO₃)₂ water types to Na-Cl types.

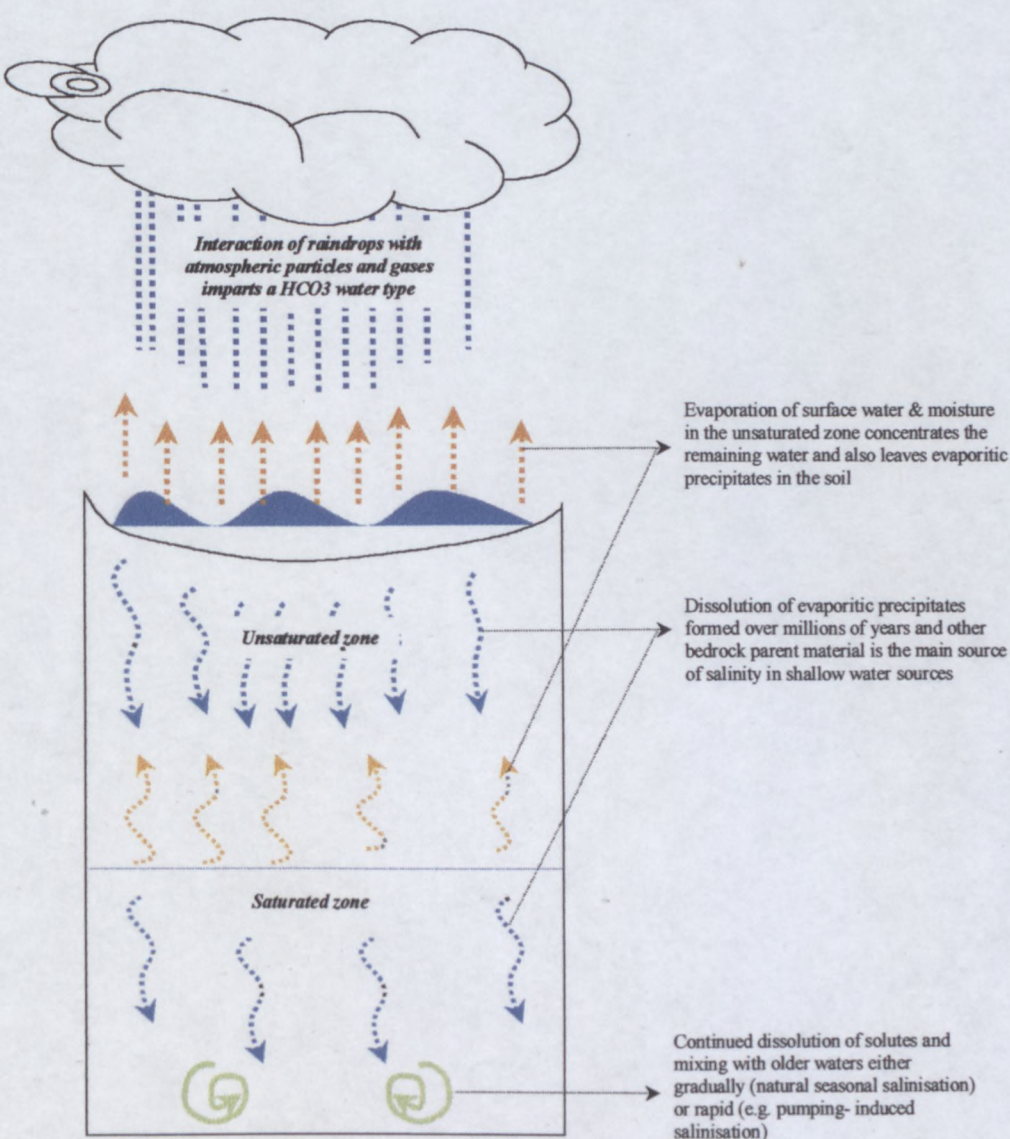


Figure 7.1. A proposed summary of the main processes and mechanisms that are responsible for groundwater salinisation in ephemeral river-based water sources in arid environments.

Ephemeral rivers and their associated groundwater reserves are in most cases the only source of freshwater in arid environments and as a result, people in these areas often experience a seasonal shortage of potable water due to the above-stated salinisation. This research would serve to inform water managers and planners in these regions of a problem that is so often overlooked in the planning of water supply strategies and infrastructure in these regions particularly in rural areas.

7.1.2 Collection of atmospheric moisture

7.1.2.1 *Chemistry of fog water*

Fog in many parts of the world is generally contaminated due to industrial activities and continues to be of major concern to atmospheric scientists as a carrier of pollutants particularly in industrialised areas where it is often contaminated by direct gaseous emissions from industry, and photochemical smog.

The study found that Namib fog is generally of low chemical content. The TDS of the collected fog water varies from about 70 to 1000 mg/l and is thus of 'A' quality drinking water according to the WHO-derived Namibian Drinking Water Quality Guidelines (NDWQG). The variation in TDS depends on the cleanliness of the collector surface and therefore, lower fog water TDS can be obtained by incorporating fog collector-cleaning mechanisms/devices that would rinse the collector surface prior to collection and storage of collected fog water for drinking purposes. These kind of devices would be beneficial to fog collection schemes throughout the world because even where dust accumulation on the collector is not a major problem, these collectors also attract birds that soil the collector material with faecal deposits, leaving them in unhygienic conditions.

The data on groundwater salinisation from this study and that on fog deposition from earlier investigations indicate that the period of high groundwater salinity coincides with that of peak fog deposition. This coincidence is ideal for mixing the collected fog water with the saline groundwater to supply potable water to people in these areas and could be explored as one solution to the problem of seasonal groundwater salinisation. This could also apply to other areas other than the Namib and should therefore be explored.

7.1.2.2 Atmospheric moisture collectors

The investigations of surface properties of fog harvesting beetles and experiments with small prototype collectors show that it is possible to increase fog collection in collectors are currently used in fog water supply schemes. The results also indicate some of the possible options that could be investigated for large-scale water supply and would stand to benefit current and future development of efficient fog collectors for large-scale water supply.

The results show that it is possible to use other polymeric greenhouse shade netting in cases where the polypropylene mesh that is used in Standard Fog Collectors (SFC) is not available. The best weave and Percentage shade coefficient for fog collectors in low elevation areas is an equilateral triangle shaped weave with a 35 - 40 Percent shade coefficient, however, experiments with an extractor fan-based collector indicate that a higher shade coefficient could be more appropriate in high elevation areas because fog deposition in these areas occurs at higher wind speed.

The investigations of surface properties namely, contact angles; hydrophobic and hydrophilic properties, and experiments with various prototypes show that it is possible to increase fog collection in the fog collectors as they exist today.

Hydrophobic surface conditions, as found on the cuticles of fog-basking beetles (*Onymacris unguicularis* and *Onymacris bicolor*), would enhance formation of large fog droplets and runoff on the collector surface, Figure 7.2.

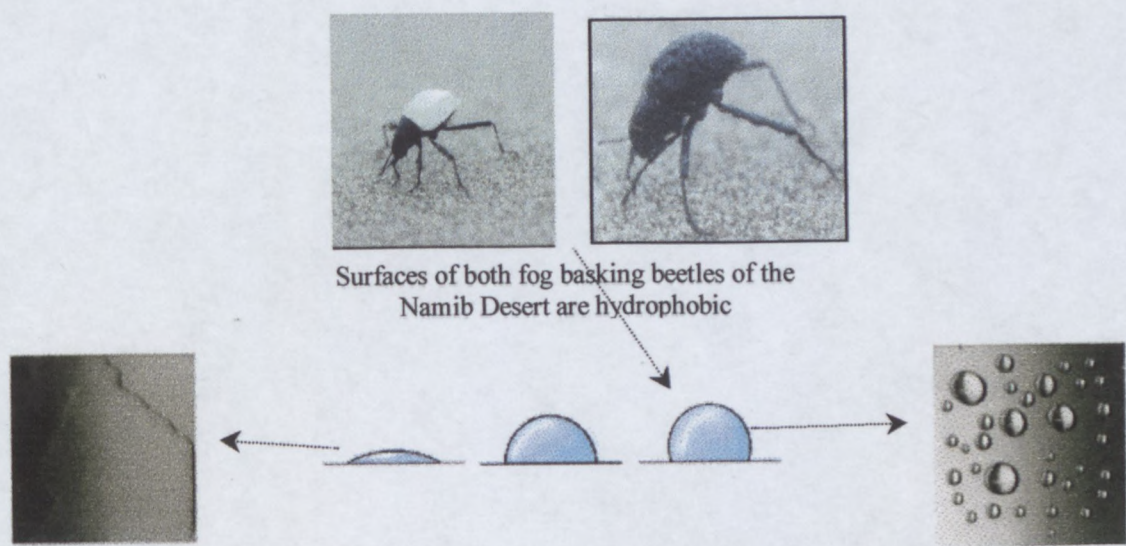


Figure 7.2. The analysis of both species of fog harvesting beetles in the Namib Desert show that they have hydrophobic surface conditions.

These kind of surface properties can be incorporated in fog collectors in order to increase their efficiency. These results also explain why some of the fog collector material in earlier fog collection trials as reported in e.g. Schemenauer and Cereceda, 1994, (see section 3.3) did not prove successful because the intercepted fog water does not runoff due to high adhesive forces between the droplets and the collector surface. Instead, the intercepted droplets forms a film on the collector surface.

The results also show that fog collection can be increased up to three times in cases where the speed at which fog passes through the collector surface is increased with a fanning device.

The cooling system prototype collects an equal amount of fog water as the passive polymeric fog collector mesh during fog events (i.e., when the relative humidity is 100%), however, it is also collects a comparable yield even when there is no fog, up to a relative humidity of about 40%.

A combination of the extractor fan and the cooling system collector would improve on the performance of existing collectors, however, such a collector would have a higher cost of water production, depending on the choice of material and technology, Figure 7.3.

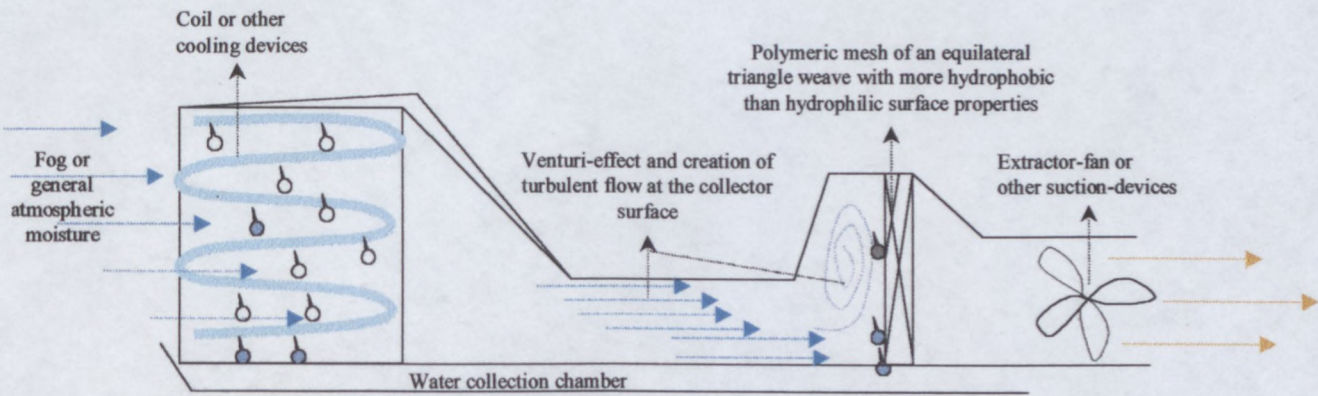


Figure 7.3. The proposed combined extractor fan and cooling system collector.

It should further be noted that these prototypes only serve to investigate the effect of varying some of the important parameters on fog collection. That any actual implementation in existing fog collectors would require feasibility studies that should also investigate cheaper alternative material and designs to replace what was used in the prototypes.

7.1.3 Desalination

The results of low-pressure (6 bar) desalination experiments with a small polyamide membrane reverse osmosis unit from Mineral Water Development show that it is possible to operate the unit with a solar-driven pump. The unit would produce about 4600 litres per day (l/day) of 500 mg/l TDS product water.

The actual PV-operated unit could produce only between 60% to 80% of the total volume obtained during the laboratory tests considering that peak performance might not be attainable in field conditions due to variation in the relevant climatic factors (e.g. cloud cover) and the long-term performance of the membrane. However, even this production exceeds that of similar world-leading remote area RO systems in the Canary Islands and Australia (e.g. figure 7.4), and is well within the average daily water demand of villages in the Namib Desert which varies between 700 to 2300 litres per village per day. The average number of people per village and per capita water demand varies between 10 - 50 people per village and 22 - 30 litres per day, respectively.

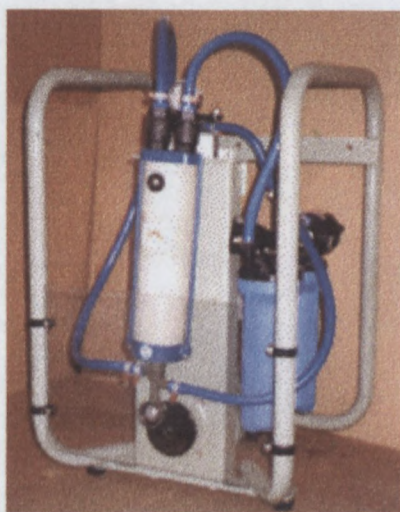


Figure 7.4 One of the world's leading small scale photovoltaic RO systems in Australia that delivers about 400 litres per day. (Source: Goen Ho, 2001- section 3.2.1).

The operating pressure and daily duration of operation of the unit can be enhanced by using energy recovery equipment that would recycle about 50% of total energy used, which would otherwise be lost in the brine. The use of existing natural elevation differences to increase the feedwater pressure prior to desalination could also reduce this operating pressure. These and many other small adjustments could be incorporated at a relatively low cost in order to increase the water production of this unit.

The experiments with solar distillation basins made with cheap frames and insulation material show that it is possible to reduce the unit cost of water production in this type of units sufficiently to allow for implementation in poor remote rural areas. These units would cost about US \$75 as opposed to the US \$ 400 - US \$700 unit cost that is reported in literature, and therefore indicate the merits of experimenting with alternative material in order to reduce construction costs. However, even the reduced cost of water production is still much higher than that of a PV-operated RO unit if one is concerned with village water supply as opposed to individual households.

The results indicate that other alternatives to solar stills could often be more cost-effective and that other options, particularly photovoltaic powered reverse osmosis need to be given more attention.

7.2 Recommendations

- ❑ The seasonal shortage of potable water in arid regions is generally overlooked in issues of arid land water supply, however, this is an important aspect that needs to be considered in all water supply strategies for these regions.
- ❑ Fog water can be used directly for drinking purposes, however, the study strongly recommends mixing it with the saline groundwater in order to make more potable water available to the users.
- ❑ Cleaning of the fog collector surface prior to fog collection would improve the quality of collected fog water and also increase the amount of potable water in cases where fog and saline groundwater mixing is implemented. Alternatively, cleaning devices can also be considered whereby the runoff channel to the water storage container has a sluice that requires a few litres to open, which would thus serve to direct the initial runoff (rinse-water) away from the storage compartment.
- ❑ Atmospheric moisture is a feasible alternative source of freshwater in the Namib Desert that needs to be given more attention. More research into passive atmospheric collectors could make this source of water a reliable option for larger communities and even for supplementing freshwater sources in coastal urban centres in arid environments where fog deposition often exceeds rainfall several times e.g. about seven times along the coast of Namibia.
- ❑ The study demonstrates that there are often many opportunities that develop in the membrane and desalination industry that could benefit remote rural area water treatment systems, however, these are never capitalised on because they are mainly targeting the large scale desalination industry. The study therefore strongly recommends that scientists, engineers and water managers in these regions should continuously monitor developments in the larger desalination and water treatment industry for technologies and other discoveries that can be modified for water supply to remote areas.